Synthesis and properties of optically active oxa[9]helicene derivatives through optical resolution of helical quinone derivatives

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Ph.D.) in Synthetic Organic Chemistry.

宇都宮大学
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Ph. D. Thesis

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DEDICATED

To my beloved mother

All that I am, or hope to be,
none of this would have been possible
without her prayer and support.

Ph.D. Thesis Title

Synthesis and properties of optically active oxa[9]helicene derivatives through optical resolution of helical quinone derivatives

ABSTRACT

The chemistry of screw shaped helical molecules is going to be a fascinating advance research field in many ways. Helicene molecules possess π-conjugated ortho-fused aromatic rings and have exceptional optical and electronic properties as well. In general, helicene molecules are classified in two different categories one is carbohelicenes and another one is heterohelicene. Early research work on helicene chemistry was mainly focused on carbohelicenes but, recently due to interesting properties and wide range of applications, research on heterohelicene (e.g. thia-, sila-, aza- and oxahelicene) has gained tremendous interest. According to the literature survey, it is shown that, incorporation of heteroatoms in the helical skeleton enhances the optical and electronic properties of the molecules. For the last 20-25 years, significant surveillance has been committed to thiahelicenes and azahelicenes. However, in case of oxahelicenes less attention was paid compare to other heterohelicenes. This thesis deals with different effective synthetic methods of the synthesis of helicene like molecules and oxa[9]helicene derivatives. We have also successfully applied some of the amphiphilic oxa[9]helicene derivatives on Langmuir–Blodgett (LB) film formation. This thesis paper is divided into several chapters and each chapter deals with new synthetic approach. Chapter 1 highlights the overview of the synthesis of helicene and helicene like molecules using different fundamental techniques. Chapter 2 describes the synthesis of quinone derivatives, which are the sole starting materials of this whole research by oxidative coupling reaction of 2-hydroxy benzo[c]phenanthrene derivatives. Chapter 3 deals with the synthesis of BIPOL ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) type derivatives using 5% Pd-C catalyst from our sole compound quinone derivatives. In this chapter, the molecular conformation is also confirmed by X-ray crystallographic data analysis. Chapter 4 concerns the synthesis of 9-halo-substituted oxa[9]helicene derivatives and unexpected dibromo spiro lactone compound from helical quinones. The unique structure of the spiro-lactone was confirmed by different spectroscopic data analysis and finally the molecular conformation was confirmed by X-ray crystallography. Chapter 5 shows the synthesis of

amphiphilic oxa[9]helicene derivatives and concerns the enantiomeric resolution and fundamental optical properties. Chapter 6 narrates the synthesis of optically pure quinone derivatives using chiral reagents and finally, Chapter 7 outlines the application of amphiphilic oxa[9]helicene derivatives on Langmuir–Blodgett (LB) film.

DECLARATION

The scientific work described in this Thesis was carried out in the Graduate School of Engineering under Department of Innovation Systems Engineering at the Utsunomiya University between October 2013 and March 2017 for the fulfillment of Doctor of Philosophy degree in Organic Chemistry. Unless otherwise stated, it is the work of the Author and has not been submitted in whole or in part in support of an application for another degree or qualification at this or any other University or institute of learning.

Mohammad Shahabuddin

Signed:_____ Date:_____

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Alhamdulillah; all praise to the most forgiving, most generous, most merciful Allah. Although life has its various challenges, it is still precious in many ways. Ya Allah, I am satisfied because your plans are better than my dreams, so whatever comes to my way, ya Allah I am satisfied.

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LIST OF SYMBOLS AND ABBREVIATION

***p*-TSA**	*p*-Toluenesulfonic acid
NBS	N-Bromosuccinimide
NIS	N-Iodosuccinimide
NCS	N-Chlorosuccinimide
DCM	Dichloromethane
DCE	1,2-Dichloroethane
THF	Tetrahydrofuran
DMSO	Dimethyl sulfoxide
DMF	N,N-Dimethylformamide
EtOAc	Ethylaetate
EtOH	Ethanol
MeOH	Methanol
MeCN	Acetonitrile
Et_3N	Triethylamine
TMEDA	Tetramethylethylenediamine
DBDMH	1, 3-Dibromo-5,5-dimethylhydantoin
NBSa	N-Bromosaccharin
NBTh	N-Bromophthalimide
PTB	Pyridinium tribromide
DDQ	2, 3-Dichloro-5, 6-dicyano-1,4-benzoquinone
FT-IR	Fourier Transform Infrared Spectroscopy
NMR	Nuclear Magnetic Resonance
TG-DTA	Thermal Gravimetric-Differential Thermal Analysis
CD	Circular Dichroism
HPLC	High Performance Liquid Chromatography
UV-Vis	Ultraviolet–visible
PL	Photo luminescent
Calc.	Calculated
HRMS	High Resolution Mass Spectrometry
δ	Chemical Shift

TMS	Tetramethylsilane
Δε	Extinction Coefficient (or, Molar Absorptivity)
$[\alpha]_D$	Specific Optical Rotation
[Φ]	Molar Optical Rotation
TLC	Thin Layer Chromatography
ORTEP	Oak Ridge Thermal Ellipsoid Plot
EI	Electron Impact
FAB	Fast Atom Bombardement
Å	Angstrom
J	Coupling constant
hv	Light
Me	Methyl
Et	Ethyl
^{t}Bu	*tert*-Butyl
m/z	Mass to charge ratio
d	Doublet
dd	Doublet of doublet
s	Singlet
m	Multiplet
t	Triplet
SiO_2	Silica gel (230-400 mesh, 0.04-0.063 mm)
rt	Room Temperature
$CDCl_3$	Chloroform-d
ppm	Part(s) per million
Hz	Hertz
mmol	Millimole (s)
mg	Milligram (s)
ee	Enantiomeric excess

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CHAPTER 1

Literature review on helicene and helicene like molecules

CHAPTER 1

1 INTRODUCTION

1.1 PREFACE

Research on helicene and helicene like molecules is not a new idea. For the last 100 years, helicene chemistry evolves as one of the interesting topic of advance research. Helicenes and helicene like molecules attracting more and more attention due to their amazing properties and application in different field of modern science. One of the interesting features of helicene is its chirality. The minimum requirement for helicity to occur is the existence of five *ortho*-annulated rings. When benzene rings inserted into the helical structure at *ortho*-position, the terminal rings impose steric strain to each other and the molecules are no longer be a flat shape, it turns into screw-shape to release internal strain.[1] The screw-shape of helicene framework is the main reason of its chirality although helicenes do not have any asymmetric carbon centers. The chirality of helicene results clockwise and anti-clockwise helical conformers that are not super-imposable.

In general, helicene molecules are classified in two major different categories. One is carbohelicenes and another one is heterohelicenes (Figure 1.1). However, at the beginning of helicene chemistry research, most of the scientific work were mainly centered on carbohelicenes synthesis and figure out their versatile applications. It is always being a challenge to synthesis large helicenes because, when the helical rings increase the internal strain is also increase and to remove the internal strain is quite difficult. For a long time, [14]helicene was the largest carbohelicenes so far synthesized by Martin and Base in 1975.[2] After nearly four decades Fujita *et. al.* reported that they have successfully synthesized [16] helicene by conventional oxidative photocyclization process where they used [2]+[1]+[1]+[2]+[2]+[1]+[1]+… sequences (e.g. "[n]" and "+" denoted as *ortho*-fused [n]helicene subunits and vinylene linkers) rather than [1]+[1]+[1], [2]+[2] and [2]+[1]+[2] sequences where benzoperylene and anthracene framework were formed as the major product. Although the product yield was not good (only 7% yield) but their work shows the simplest way to synthesis of higher helicene which is good for helicene chemistry.[3]

However, as the time passing by, literature survey shows the first growing interest on hetero helicene compounds where a heteroatom (e.g. O, S, N, Si etc) inserted into the fused ring

system. Insertion of heteroatom in fused ring system is expected to contribute reasonably high HOMO energy level.[4] This unique feature is highly attracted the researcher's attention for further improvement in many fields of material sciences including organic light emitting diode (OLED) materials,[5] asymmetric catalysis,[6] chiral molecular recognition,[7] molecular mechines,[8] liquid crystals[9] and so on.

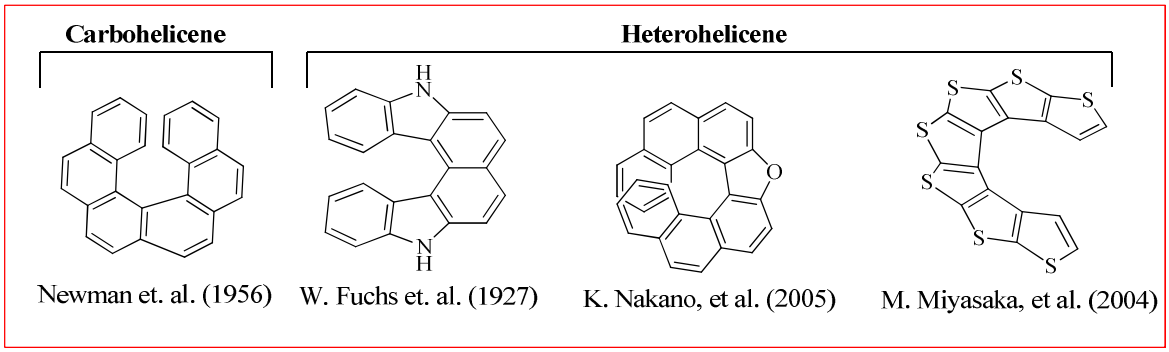


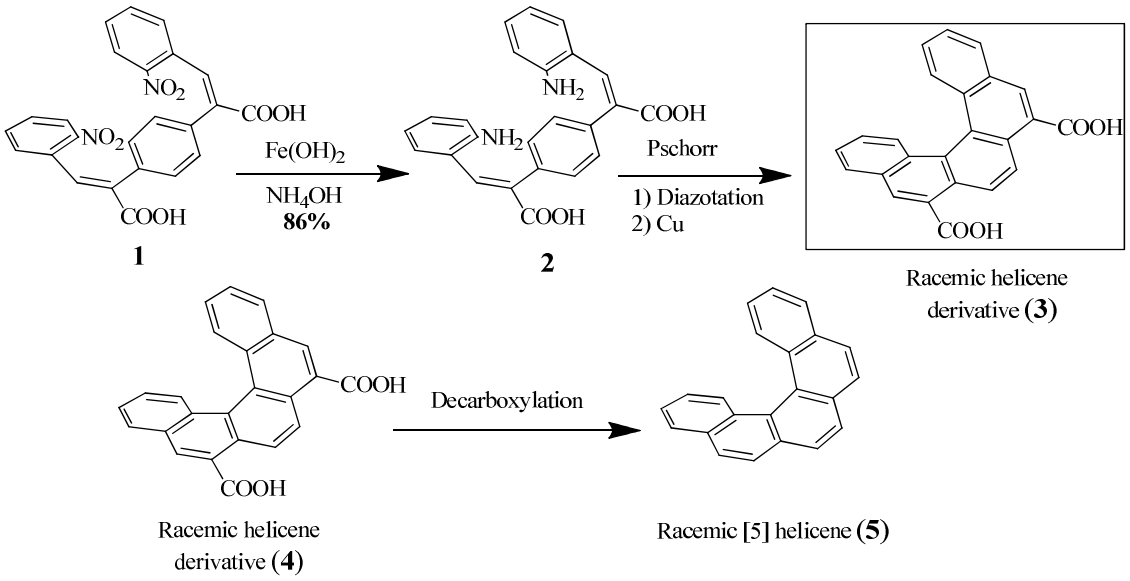
Figure 1.1 Classification of helicene molecules

1.2 LITERATURE REVIEW ON CARBO HELICENES

Carbohelicenes are generally incorporated a helical, distorted, conjugated polyaromatic ortho-fused benzenoid rings system, which is a fundamental molecular characteristics of this class of compounds. For the last 100 years different sort of synthetic approaches was done by different research groups around the world. Among them photocyclization of stilbene type derivatives studied the most. All other methods such as Diels-Alder reaction approach for functionalized carbo helicene synthesis by Katz in 1990, benzylic-type coupling by Kharash and coworkers in 1944, carbonyl or pinacol coupling, metal catalyzed reactions, 3-oxy-cope type rearrangement by Karikomi in 2002, Friedel-Crafts type cyclizations, Hewett cyclizations and so on.

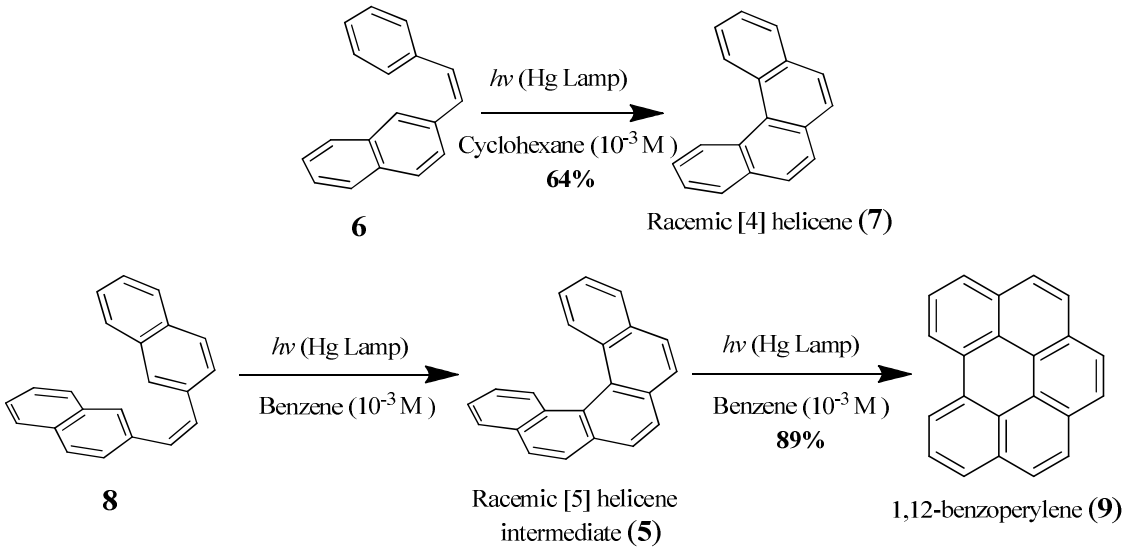
Back in the 1913, the first carbo-helicene in general [4]helicene was reported by R. Weitzenbock[10] later, the synthetic procedure was applied for the synthesis of [5]helicene in 1918. The final products [5]helicene were obtained using Pschorr reaction. The main limitation of that synthetic procedure was low yield and the final product purity has lot of

doubt because, during the reaction a competitive linear isomer was also form and which is very hard to remove from the desire product (Scheme 1.1).[11]



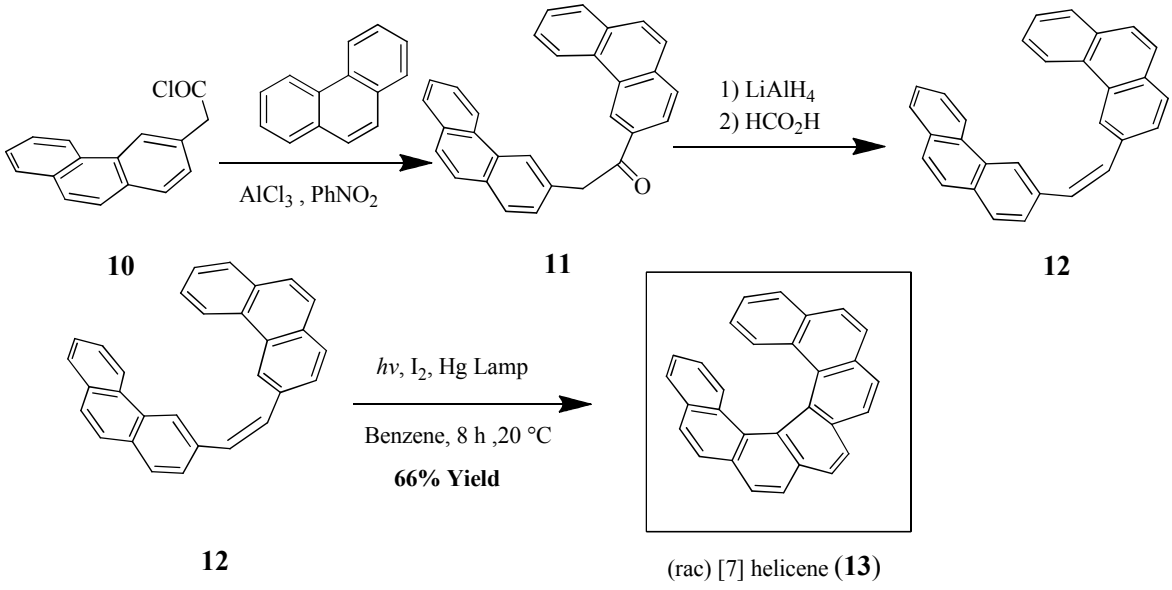
Scheme 1.1 First synthesis of [5]helicene in 1918 by a Pschorr reaction

The major breakthrough for the synthesis of carbo-helicene happened in 1967 by Scholz *et al.* They introduced the renown photochemical reaction for the formation of [4]helicene (Scheme 1.2). At the same report they also described the photosynthesis of 1,12-benzoperylene with good yield (89%). They proposed the final product might come through rearrangement of [5]helicene (Scheme 1.2).[12]



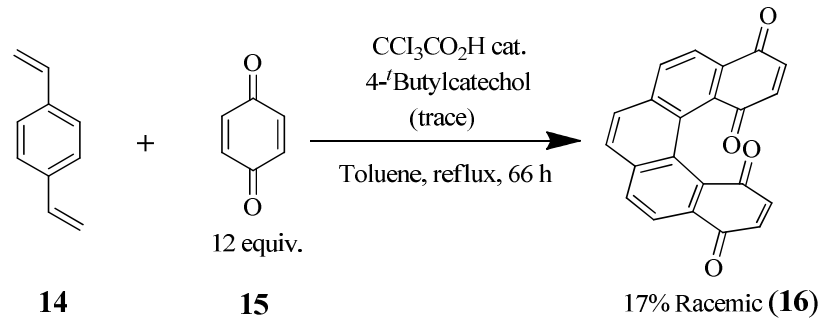
Scheme 1.2 First photosynthesis of a carbohelicene by an oxidative photocyclodehydrogenation

The historical event in helicene chemistry happened at the same year in 1967 when Martin and coworkers published their groundbreaking research work for the synthesis of [7]helicene (**13**) (Scheme 1.3). During their research they going through intensive studies on the oxidative photocyclodehydrogenation reactions for preparing polyaromatic hydrocarbons from stilbene derivatives.[13]



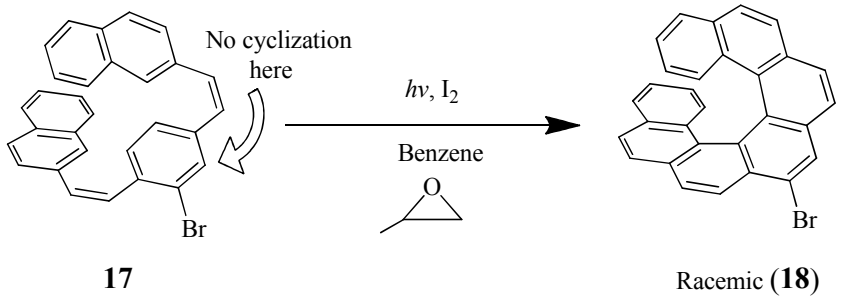
Scheme 1.3 Synthesis of [7]helicene by an oxidative photocyclodehydrogenation

Despite the importance of photocyclization reactions in helicen chemistry, it has some limitation as well. One of the major limitations is high dilution condition (~10^{-3} M). The high dilution condition is required for preventing a [2π + 2π] dimerization. Through this reaction only few hundred milligrams of helicenes can be produced. Another limitation is the continuous irradiation of light with a longer period time (7-8 h) and the irradiation must be carefully controlled. Synthesis of large amount of helicene is the next challenge for the researcher and further development of new methods are crying need. Another historical event occurred in 1990 for making large quantities of helicenes when Katz and coworkers demonstrated a peculiar Diels-Alder approach for producing functionalized [5]- or [6]helicenes (Scheme 1.4).[14]



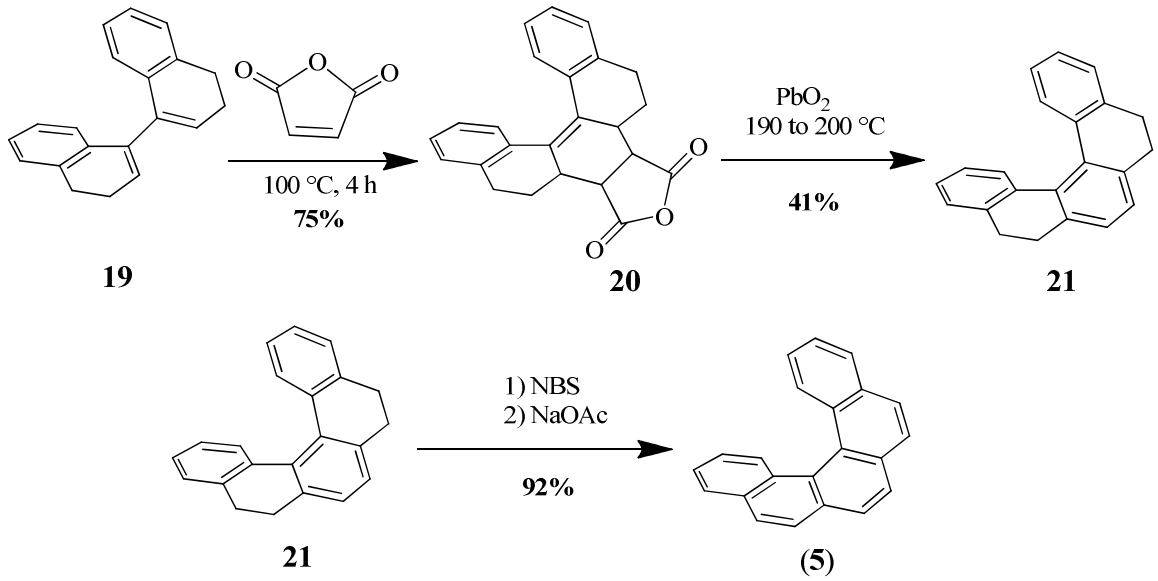
Scheme 1.4 Synthesis of a [5]helicenebisquinone (**16**)

In order to optimize the yields and to better direct the cyclization toward the desired regioisomer, the concept of a "bromine auxiliary" was used in the early work on carbohelicenes photosynthesis by Martin and coworkers (Scheme 1.5).[15]



Scheme 1.5 Bromine auxiliary method for controlling regioselectivity of photocyclization

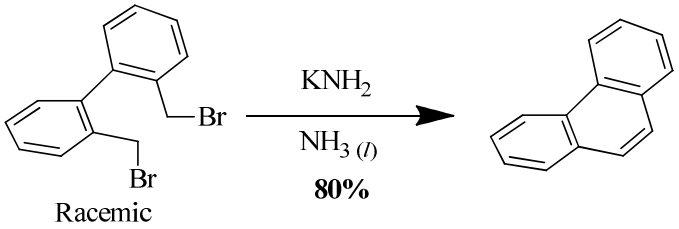
Today, the Diels-Alder strategy in helicene chemistry is by far the main synthetic choice amongst the non-photochemical methods in the literature. One of the first reports of a Diels-Alder strategy for making carbohelicenes belongs to Weidlich in 1938 (Scheme 1.6).[16]



Scheme 1.6 Synthesis of [5]helicene by Diels-Alder reaction

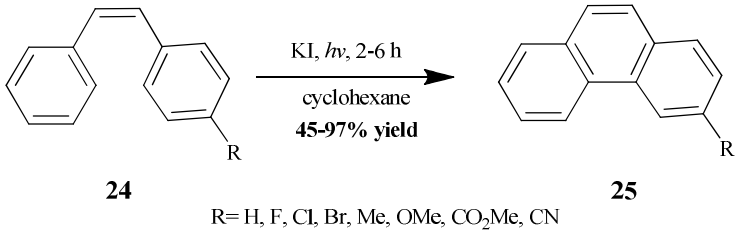
Regioselective, short and efficient syntheses of functionalized phenanthrenes still remain a challenge, especially on preparative scale. They are important building blocks for making polyaromatic hydrocarbons and carbohelicenes.

Over the years, the oxidative photocyclodehydrogenation reactions of stilbene like derivatives did not solve this problem on a large scale, but a plethora of non-photochemical methods were developed toward this goal. Among them, the "benzylic couplings" of some biphenyl derivatives were created by Kharash and coworkers in 1944. The reactivity of 2,2'-bis(bromomethyl)-l,l,-bipheny (**22**) in the presence of KNH_2 in $NH_{3(l)}$ afforded phenanthrene in 80% yield, but under strongly basic conditions (Scheme 1.7).[17,18]



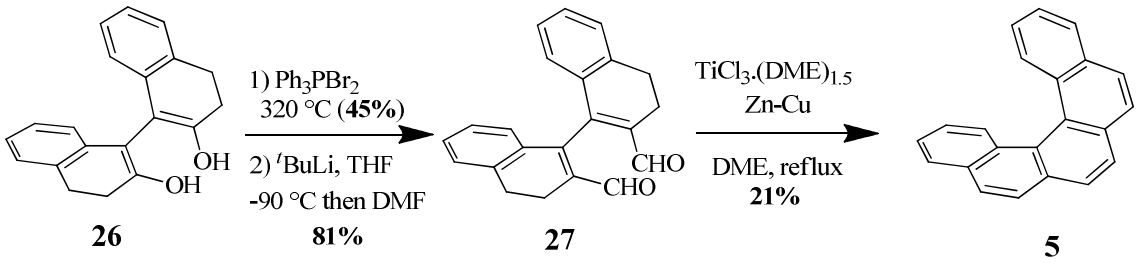
Scheme 1.7 Kharash's conditions for making phenanthrene

In 2016, Watanabe and his research group breakthrough this problem and introduce KI instead of I_2 and propylene oxide for the photocyclization of stilbene derivatives. They showed the cyclizations occurred for different types of stilbene derivatives within a short time and the product yields were excellent in most of the cases (Scheme 1.8).[19]



Scheme 1.8 Photocyclization conditions for making phenanthrene

A McMurry coupling was attempted by Gingras and coworkers for making [5]helicene from 2,2'-binaphthyl-l,l'-dicarbaldehyde (**26**). It only afforded 21% yield of the desired compound along with more polar by-products (Scheme 1.9).[20]

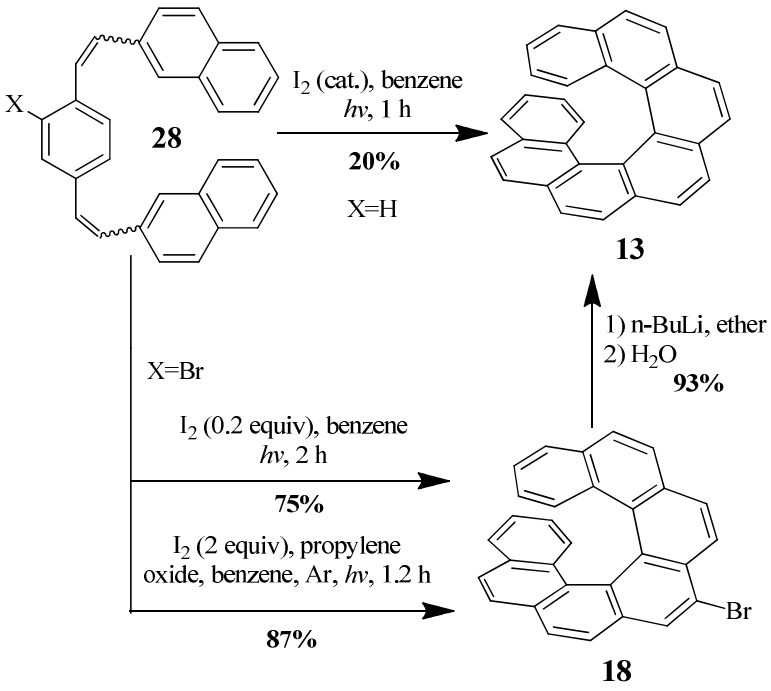


Scheme 1.9 A McMurry coupling for making a racemic [5]helicene

Among the most prominent synthetic methods for the synthesis of helicenes and their congeners is the use of transition metal catalysis. The latter could lead to a better regio- and

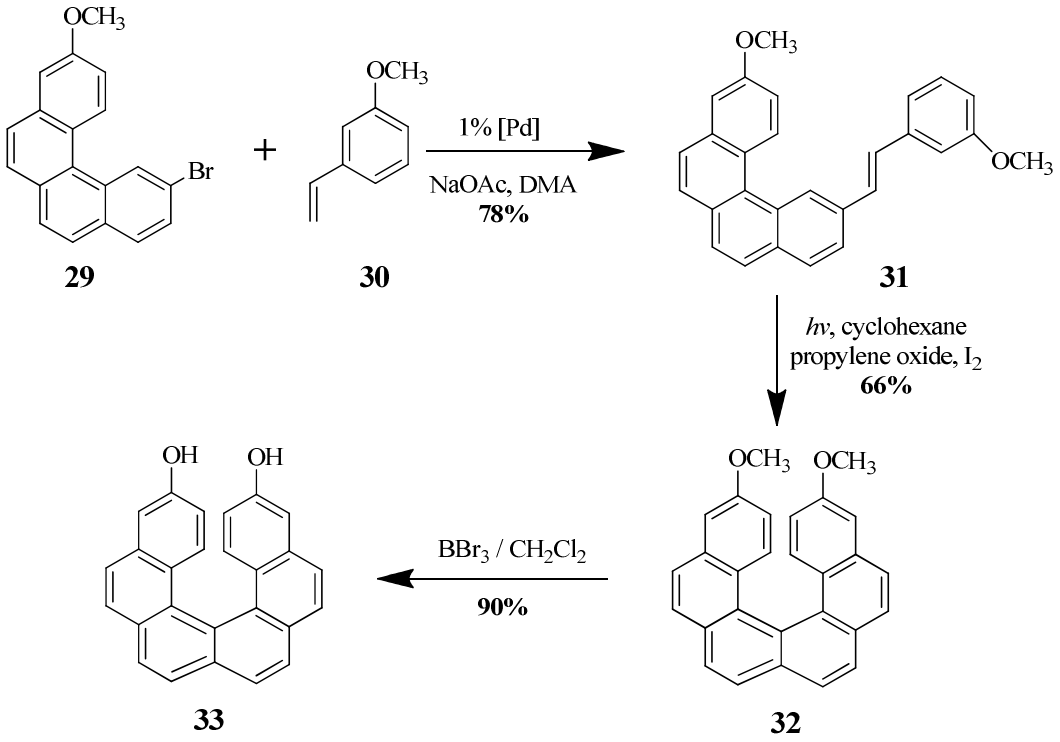
stereo control, depending on the structure of the catalyst or the substrate, and it often generates some complex molecular architecture under mild and neutral conditions in a minimum number of steps.[1]

In order to control the regioselectivity, Katz and co-workers [21, 22] developed an efficient bromine-directed photocyclization method in which helicenes can be selectively produced in 75% yield (Scheme 1.10). Katz *et al.*[23] also developed another impressive strategy using excess propylene oxide plus a stoichiometric amount of iodine in an inert atmosphere, which not only enhances the yields greatly compared with the traditional conditions for the photocyclization of stilbenes but also prevents photoreduction or photooxidative side reactions of the double bonds. This strategy has become the standard procedure for the photocyclization of stilbenoid precursors.



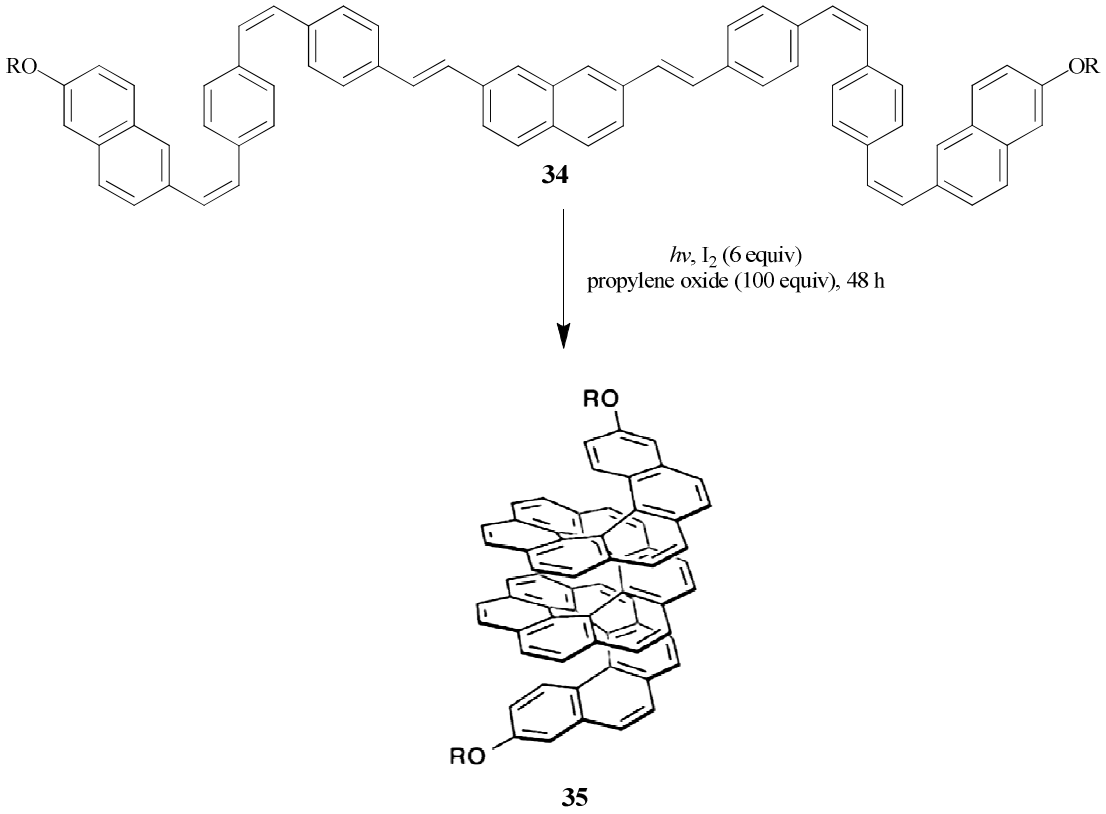
Scheme 1.10 Synthesis of [7]helicene (**13**)

A new approach to 3,14-dihydroxyhexahelicene (**33**) was described by Aloui and co-workers.[24] They envisaged a [4+1] approach involving a Mizoroki-Heck coupling of the benzo[*c*]phenanthrene moiety with an excess amount of 3-methoxystyrene using 1% of Hermann's palladacycle as the catalyst (Scheme 1.11).[25]



Scheme 1.11 Synthesis of 3,14-dihydroxyhexahelicene (**33**)

In 2015, Fujita *et al.* reported that they have successfully synthesized [16] helicene (**35**) the largest carbo-helicene so far by conventional oxidative photocyclization process (Scheme 1.12) where they used [2]+[1]+[1]+[2]+[2]+[1]+[1]+… sequences rather than [1]+[1]+[1], [2]+[2] and [2]+[1]+[2] sequences where benzoperylene and anthracene framework were formed as the major product. Although the product yield was not good (only 7% yield) but their work shows the simplest way to synthesis of higher helicene. [26]



Scheme 1.12 Synthesis of largest carbo-helicene by photocyclization process

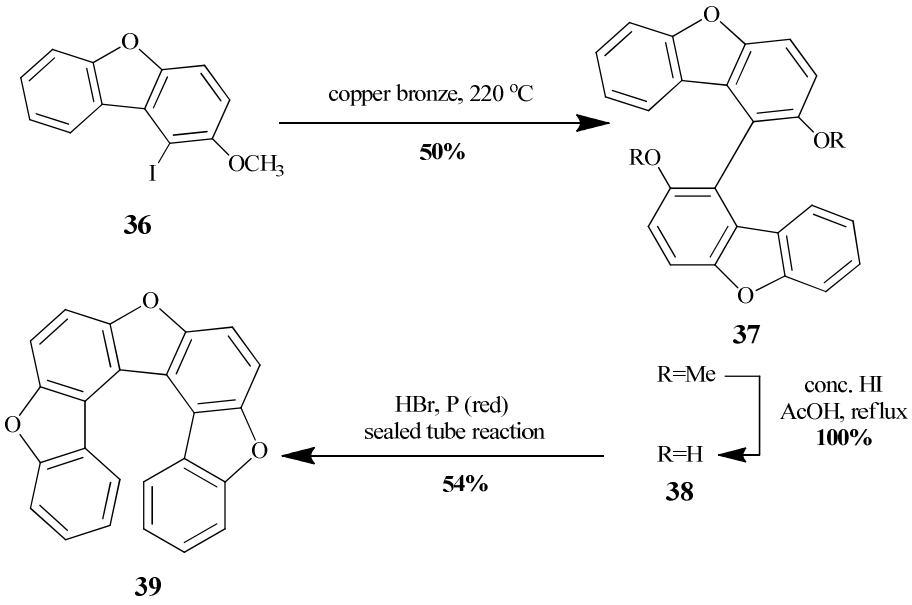
At the beginning of carbo-0helicene in 1913, namely [4]helicene, was achieved from a non-photochemical method. More than 50 years later in 1967, the photochemical approach for making carbo-helicenes took over the number of publications in the preparation of higher helicenes, starting from [5]- or [6]helicenes up to[16]helicene.

1.3 LITERATURE REVIEW ON HETARO HELICENES

Early research works were mainly concentrated on carbo-helicene molecules but now-a-days scientists are more interested on hetero-helicene compounds because, insertion of heteroatom (e.g. O, S, N, Si etc) into the fused ring system expected to contribute reasonably high HOMO energy level. This phenomena open a new for the application of hetero-helicene in different advance research field. Within the heterohelicenes, there are three major subdivisions: oxahelicene, thiahelicene and azahelicene which corresponding the heteroatoms

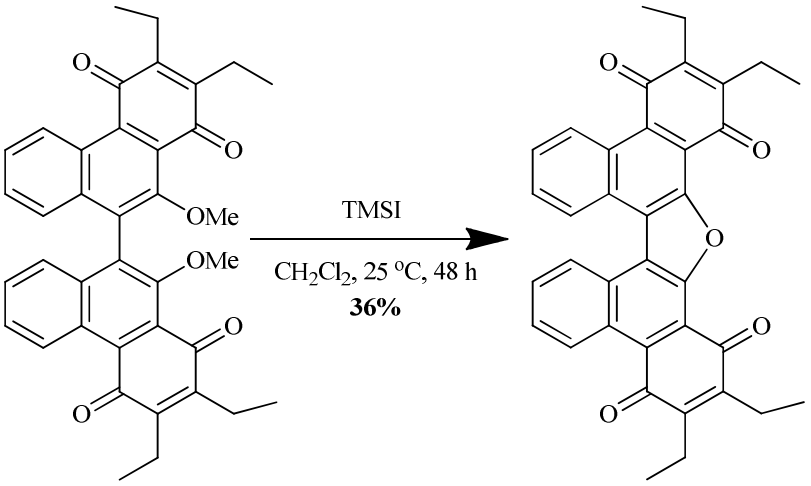
oxygen, sulfur, and nitrogen respectively. The synthesis of all of these systems is relatively difficult, usually requiring photochemical or radical reactions, which result in low yield and multiple side products. The synthesis of functionalized helicenes is even more difficult and very few literatures are available in online.

In 1973, Högberg prepared diol from dibenzofuran via Ullmann coupling, demethylation and subsequent acidification. Prolonged heating in a sealed tube resulted in ring closure producing the trioxa[7]helicene in 54% yield (Scheme 1.13).[27]



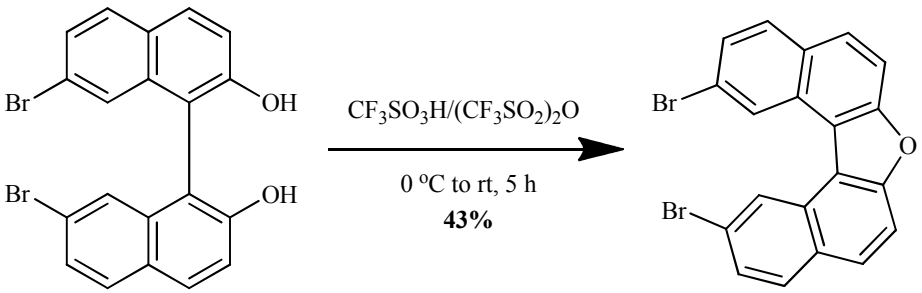
Scheme 1.13 Synthesis of trioxa[7]helicene (**39**)

In 1999, Dötz and co-workers reported a much simpler method for the synthesis of the furan fused helicene in 36% yield by adding excess TMSI to cleave the ether, followed by intramolecular nucleophilic substitution (Scheme 1.14).[28] Moreover, Dötz *et al.* also synthesized 7-oxapentahelicene (**43**) by acid-promoted ring closure in a 43% yield (Scheme 1.15).[29]



40 **41**

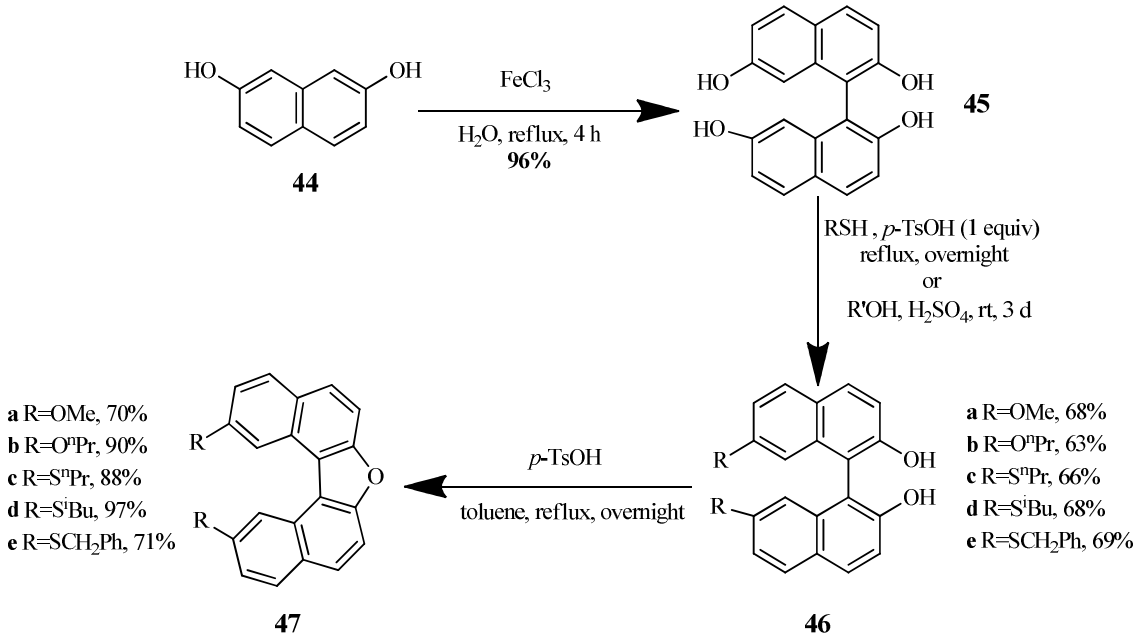
Scheme 1.14 Synthesis of substituted oxa[5]helicene (**41**)



42 **43**

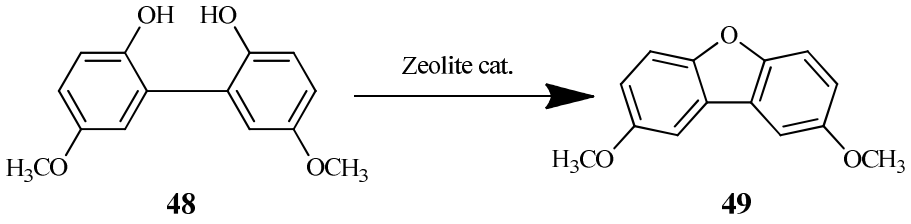
Scheme 1.15 Synthesized of 7-oxapentahelicene (**43**)

A more efficient sequence which could be easily scaled up to synthesize 2,12-disustituted-7-oxa[5]helicenes (**a-e**) from cheap commercially available materials was reported by Thongpanchang and co-workers in 2004 as shown in scheme 1.16.[30]



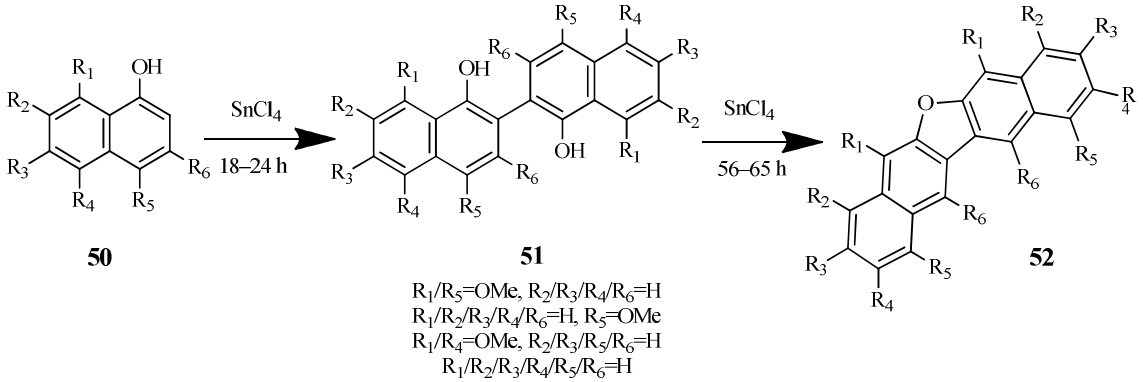
Scheme 1.16 Synthesize 2,12-disustituted-7-oxa[5]helicenes (**47**)

In 1997, Arienti *et al.* (Scheme 1.17) synthesized dibenzofuran derivatives by reaction with the zeolite catalyst.[31]



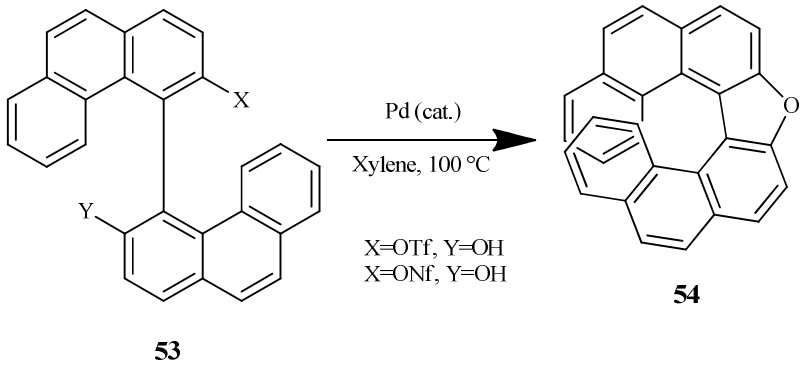
Scheme 1.17 Synthesis of dibenzofuran derivative (**49**)

Takeya *et. al.* in 2004 developed a simple method for the direct synthesis of 2,2′-binaphthols (**51**) and dinaphthofuran (**52**) framework under mild conditions, utilizing a biaryl coupling reaction via electron donor-acceptor complexes of 1-naphthols (**50**) with $SnCl_4$ (Scheme 1.18).[32]



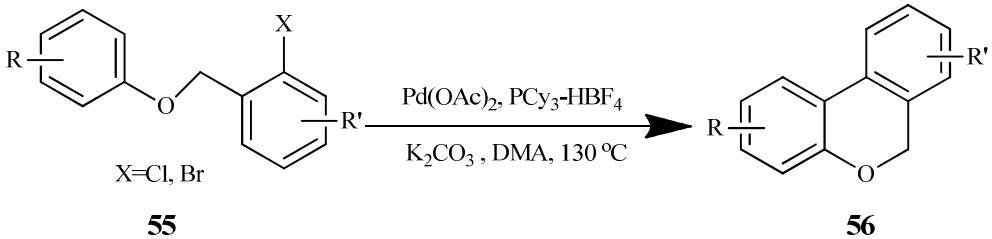
Scheme 1.18 Synthesis of dinapthofuran (**52**)

Nakano and co-workers in 2005 reported the synthesis of 9-oxa[7]helicene (**54**) as a by-product (10% yield) through the intramolecular O-arylation of 3′-hydroxy-4,4′-biphenanthryl-3-yl triflate (Scheme 1.19).[33]



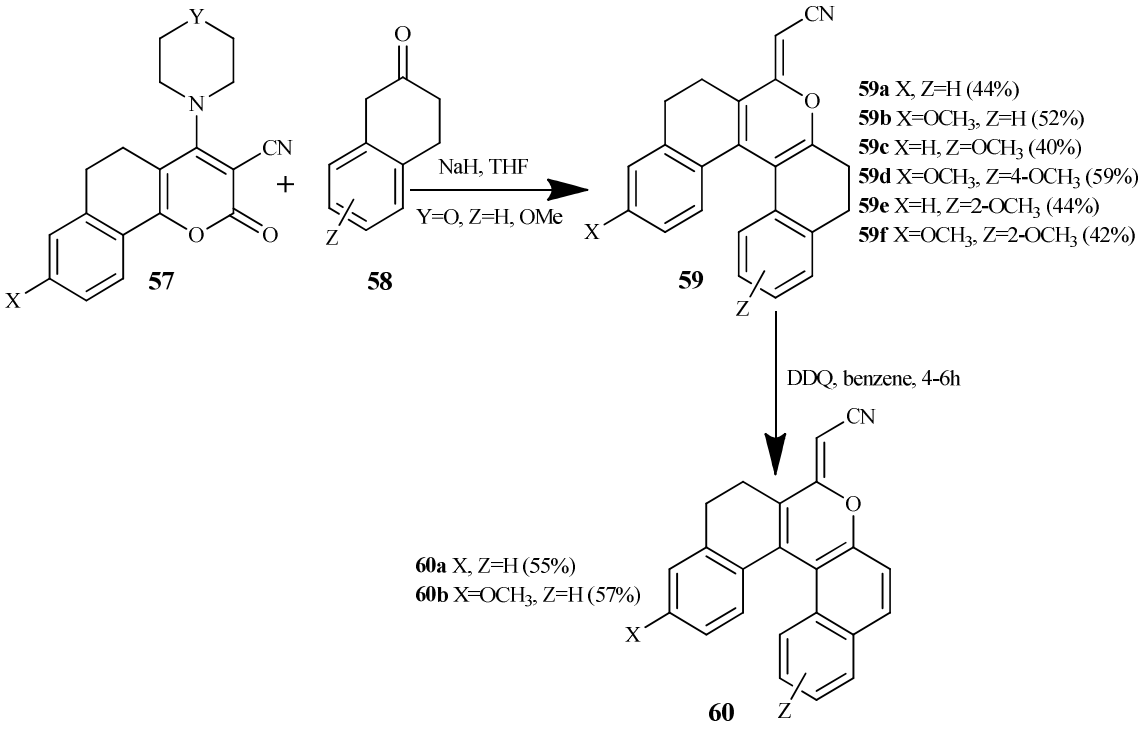
Scheme 1.19 Synthesis of 9-oxa[7]helicene (**54**)

Fagnou *et. al.* in 2006 have synthesized 7-oxa[n]helicenes (**56**) by palladium-catalyzed intramolecular direct arylation with aryl halides (Scheme 1.20).[34]



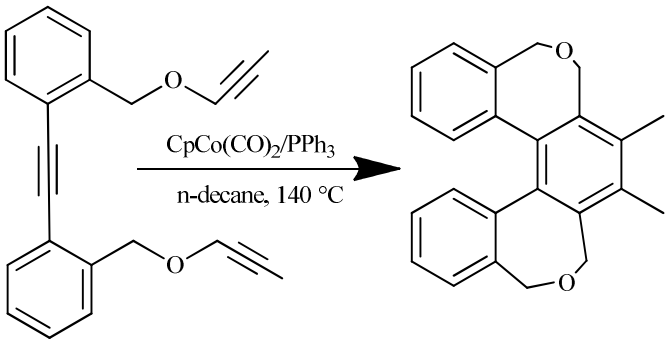
Scheme 1.20 Synthesis of 7-oxa[n]helicenes (**56**)

Atul Goel and co-workers in 2011 have developed a concise and convenient approach to the construction of partially hydrogenated oxa[5]helicenes, such as the 9,10-dihydro-7-oxa[5]helicenes (**60**) and 5, 6, 9, 10-tetrahydro-7-oxa[5]helicenes (**59**), through base-catalyzed ring transformation of suitably functionalized 2-oxobenzo[*h*]chromenes (**57**) by substituted or unsubstituted 2-tetralones (Scheme 1.21).[35]



Scheme 1.21 Synthesis of the 5, 6, 9, 10-tetrahydro-7-oxa[5]helicenes (**59**), and 9,10-dihydro-7-oxa- [5]helicenes (**60**)

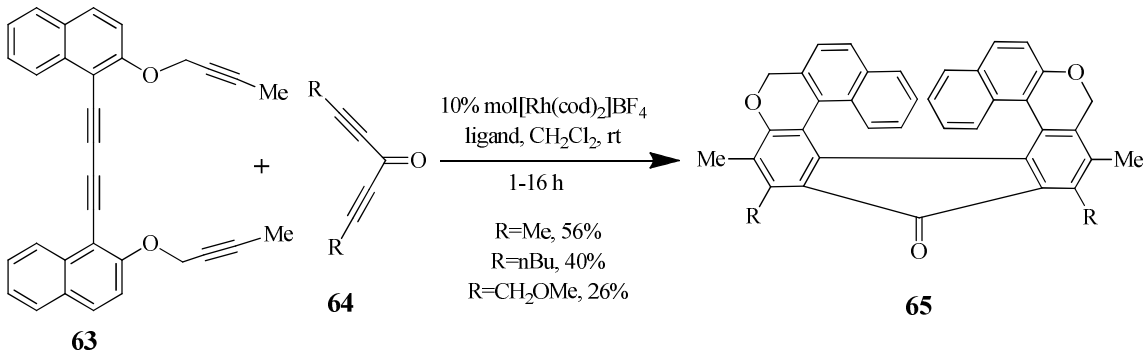
In 1998, Stara and co-workers first introduce the new strategy that is based on intramolecular [2 + 2 + 2] cycloisomerization of triynes (Scheme 1.22) by using cobalt or nickel complex.[36]



61 **62**

Scheme 1.22 Synthesis of oxa[5]helicene (**62**)

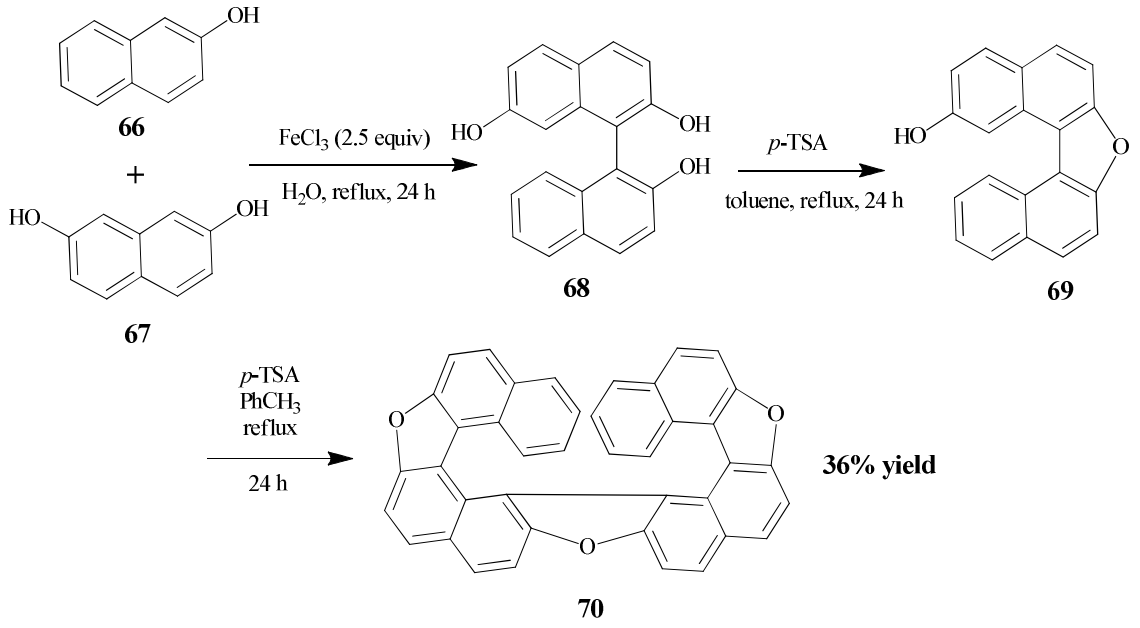
Later,Tanaka *et al.* following this pioneering work, reported a cationic rhodium(I)/chiral bisphosphine complex, which catalyzed the intramolecular [2+2+2] cycloadditions of 2-naphthol-linked triynes, leading to enantio enriched [7]helicene (**65**) like molecules in 2009 (Scheme 1.23).[37]



63 **64** **65**

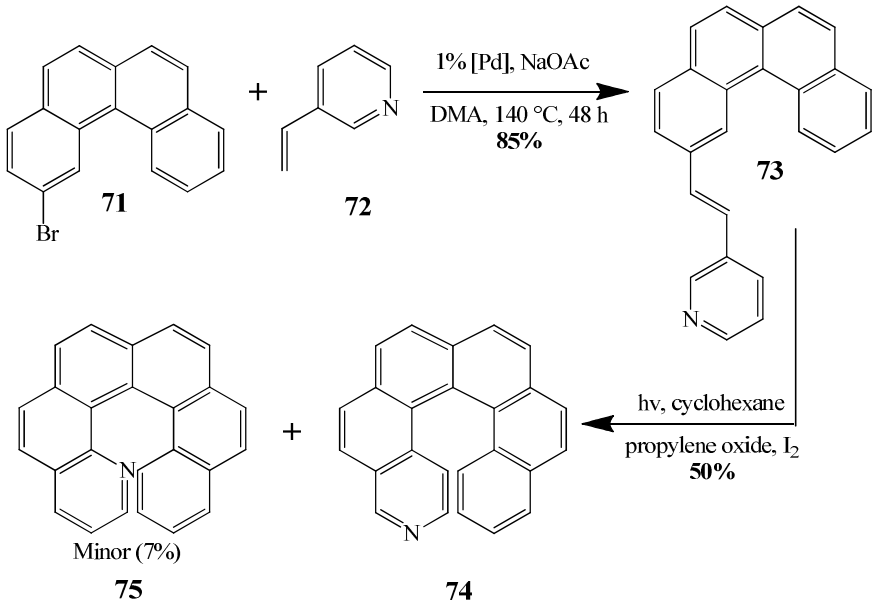
Scheme 1.23 Synthesis of [7]helicene (**65**)

Although insertion of hetero atom in helicene moiety is quite difficult but in 2015 Ashutosh V. Bedekar and his research group synthesized 7,12,17-trioxa[11]helicene (36% yield) from simple starting materials 2-napthol and 2,7-dihydroxynapthalene (Scheme 1.24) and they also shown the thermal stability and fluorescence properties of that compound as well.[38]



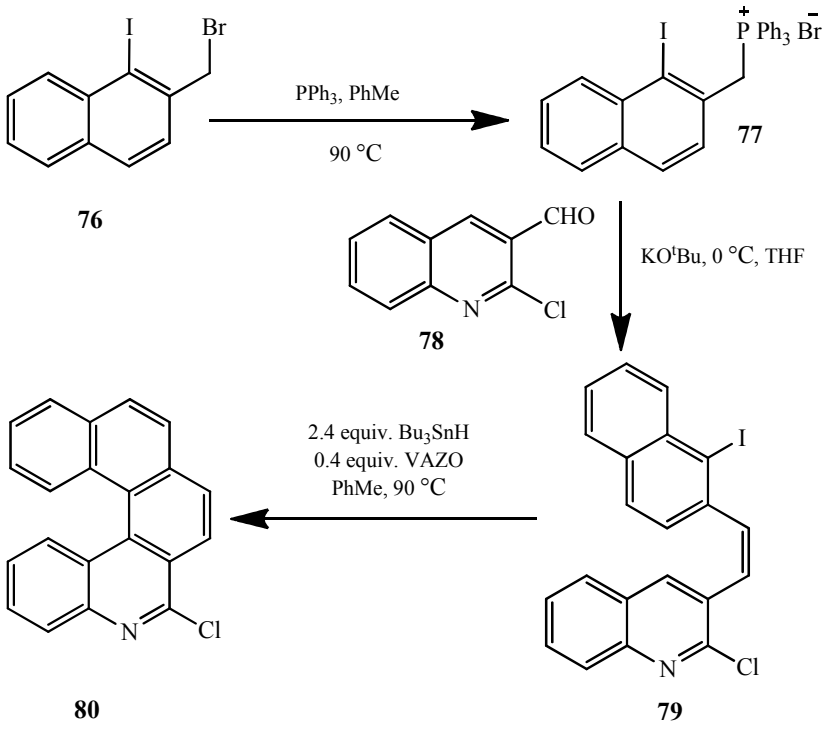
Scheme 1.24 Synthesized 7,12,17-trioxa[11]helicene

Ben Hassine *et. al.* in 2008 described a straightforward method to prepare the helically chiral framework of the hexacyclic 3-aza [6]helicene and 1-azahexahelicene (minor product) using a repetitive Mizoroki–Heck reaction / photodehydrocyclisation tandem methodology (Scheme 1.25).[39]



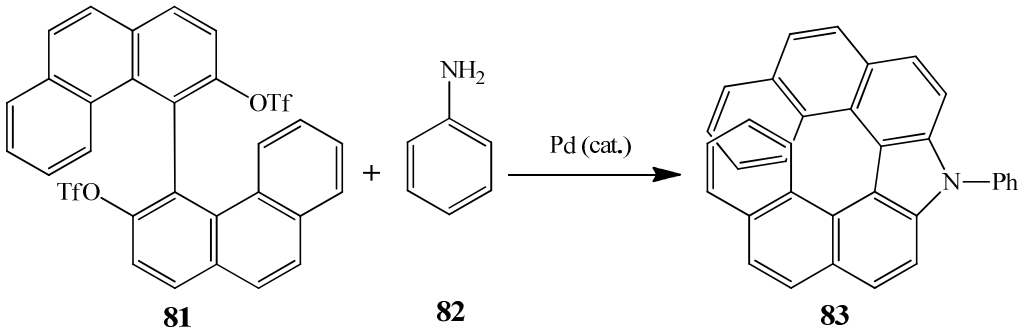
Scheme 1.25 Synthesis of 3-azahexahelicene (**74**)

Harrowven and coworkers developed a versatile synthetic method based on a Bu_3SnH mediated coupling and selective homolysis of the carbon-iodine bond by 1,1' azobis (cyclohexanecarbonitrile) (VAZO). This method was successfully applied in the high yield synthesis of 6-chloro-5-aza[5]helicene (**80**) , using cooperative *ortho* effects to control the regioselectivity of the Wittig reaction and a halide atom as a protecting group in the homolytic aromatic substitution (Scheme 1.26).[40]



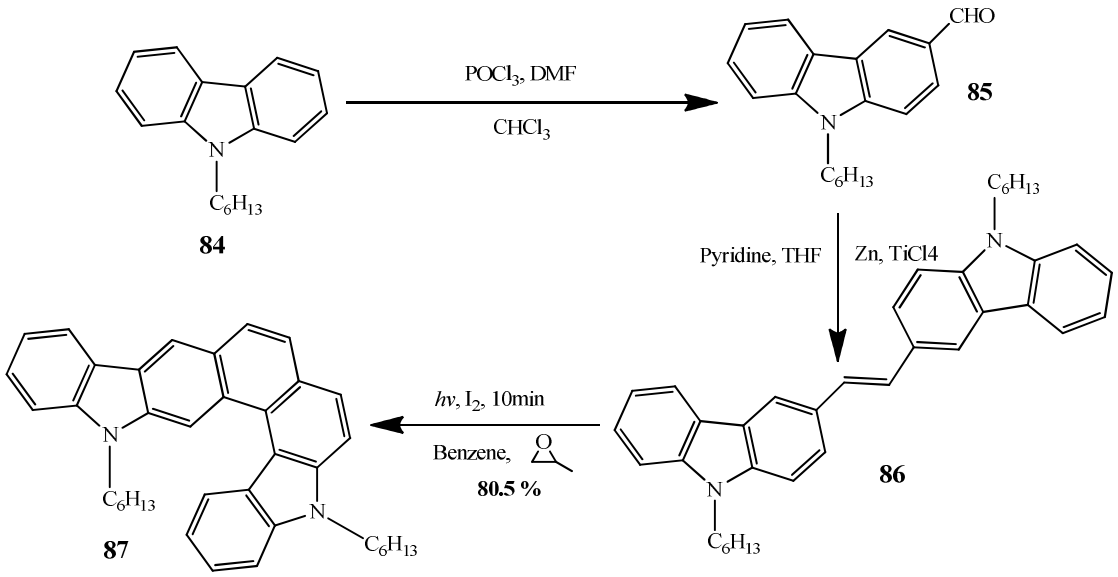
Scheme 1.26 Synthesis of 6-chloro-5-aza[5]helicene (**80**)

Nakano *et al.* used Pd complexes with xantphos and biphenyl-phosphine to catalyze coupling reactions on a variety of 2,2'-disubstituted 1,1'-diphenanthrenes. This synthesis could be applied only for obtaining the racemic aza[7]helicene (**83**) from the reaction of aniline with racemic 4,4'-biphenanthryl-3,3'-ylene ditriflate (Scheme 1.27).[41]



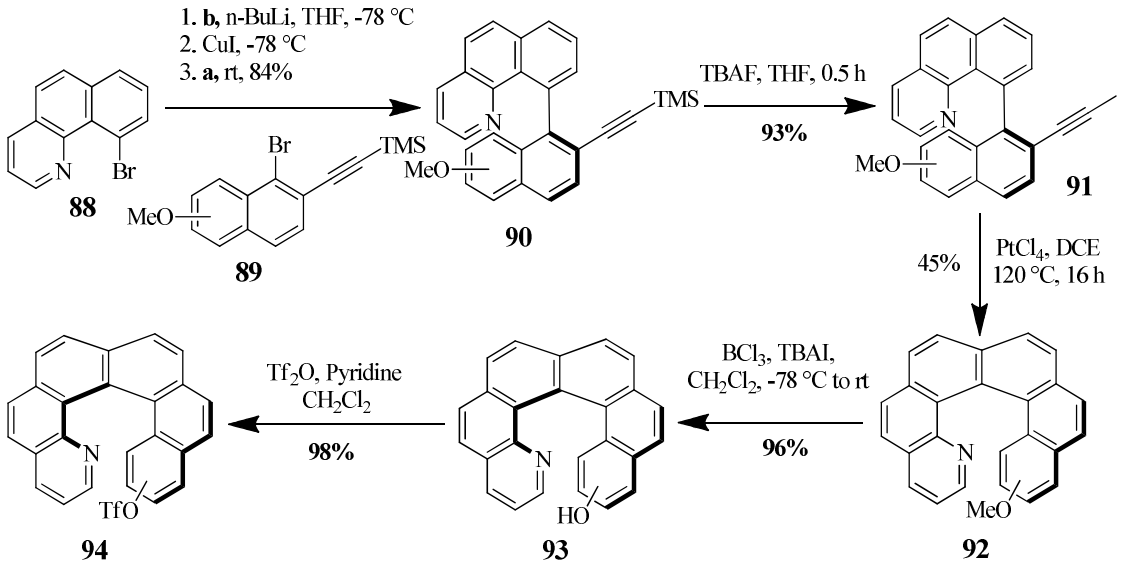
Scheme 1.27 Synthesis of racemic aza[7]helicene (**83**)

In 2012, Zhi Lie and co-workers synthesized a carbazole-based diaza[7] helicene, namely, 2,12-dihexyl-2,12-diaza[7]helicene (**87**) and used it as a deep-blue dopant emitter in an organic light-emitting diode (OLED); Scheme 1.28.[42]



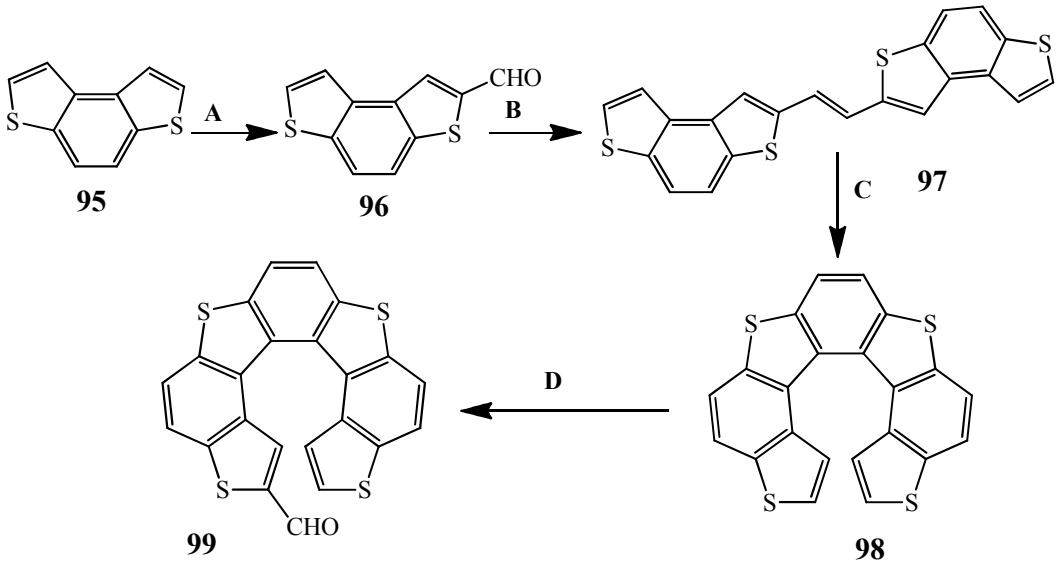
Scheme 1.28 Synthesis of 2,12-dihexyl-2,12-diaza[7]helicene (**87**)

M. J. Fuchter *et al.* in 2013 have developed a rapid and robust strategy to prepare functionalized 1-aza[6]helicenes (**94**) from 10-bromobenzo[h] quinoline and alkyne (Scheme 1.29).[43]



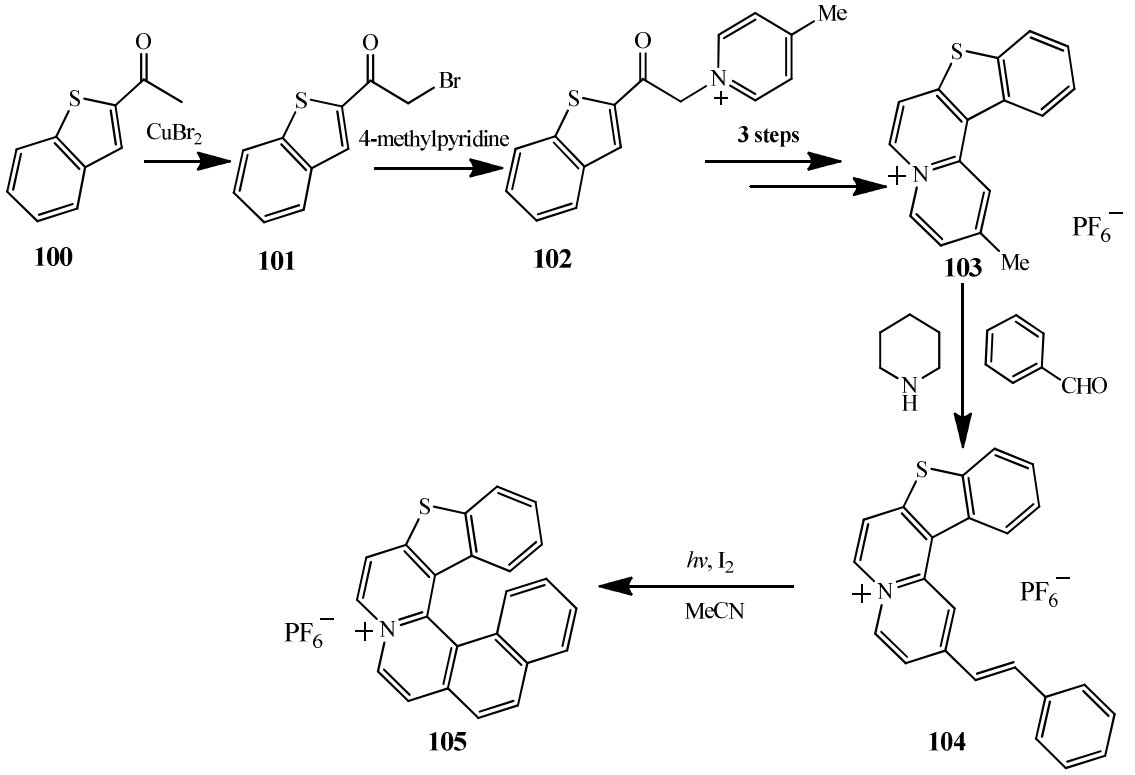
Scheme 1.29 Preparation of functionalized 1-aza[6]helicenes (**94**)

In 2003, Stefano Maiorana and his co-workers successfully synthesized α-functionalized tetrathia-[7]-helicenes (**99**) through McMurry coupling.[44]



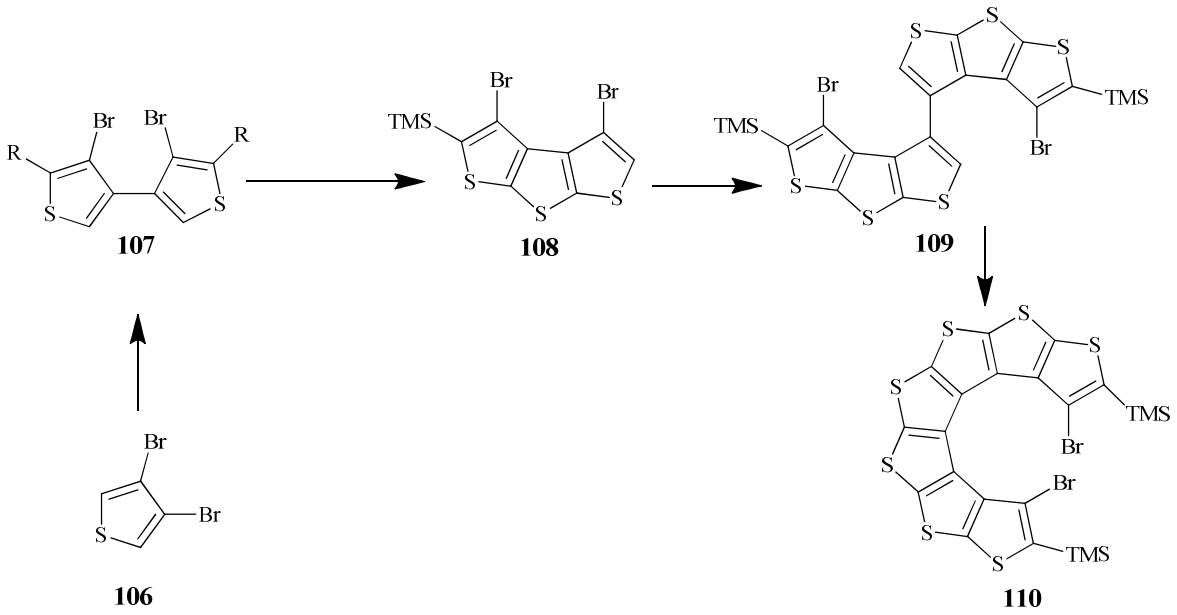
Scheme 1.30 Synthesis of α-functionalized tetrathia-[7]-helicenes (**99**)

In 2006, Kiyoshi Sato et. al. synthesized 7a-azonia-5-thia[6]helicene (**105**) from 2-acetylbenzo[*b*]thiophene. He shows, Knoevenagel condensation of 2-methylbenzothieno[3,2-*a*]quinolizinium hexafluorophosphate with benzaldehyde in the presence of piperidine gave 2 -styrylbenzothieno[3,2-*a*]quinolizinium hexafluorophosphate (**104**) in fair yield (45%). When the product **7** was irradiate with a high-pressure mercury lamp in the presence of iodine it produce 7a-azonia-5-thia[6]helicene (**8**) in good yield (63%); Scheme 1.31.[45]



Scheme 1.31 Synthesis of 7a-azonia-5-thia[6]helicene (**105**)

A novel oligothiophene (Scheme 1.32) was presented in 2000 by Rajca and co-workers, in which the thiophene rings are cross-conjugated and annulated into a helix. The synthetic route consisted of two iterations using 3,4-dibromothiophene and compound (**106**) as the functionalized starting modules. In each iteration, the modules were connected by means of a single Li/Br exchange followed by oxidative coupling with $CuCl_2$ and then annulated through the LDA (lithium diisopropylamide)-mediated dilithiation of the unprotected alpha position of the thiophene rings in **107** and **109** and further reaction with bis(phenylsulfonyl)sulfide.[46]



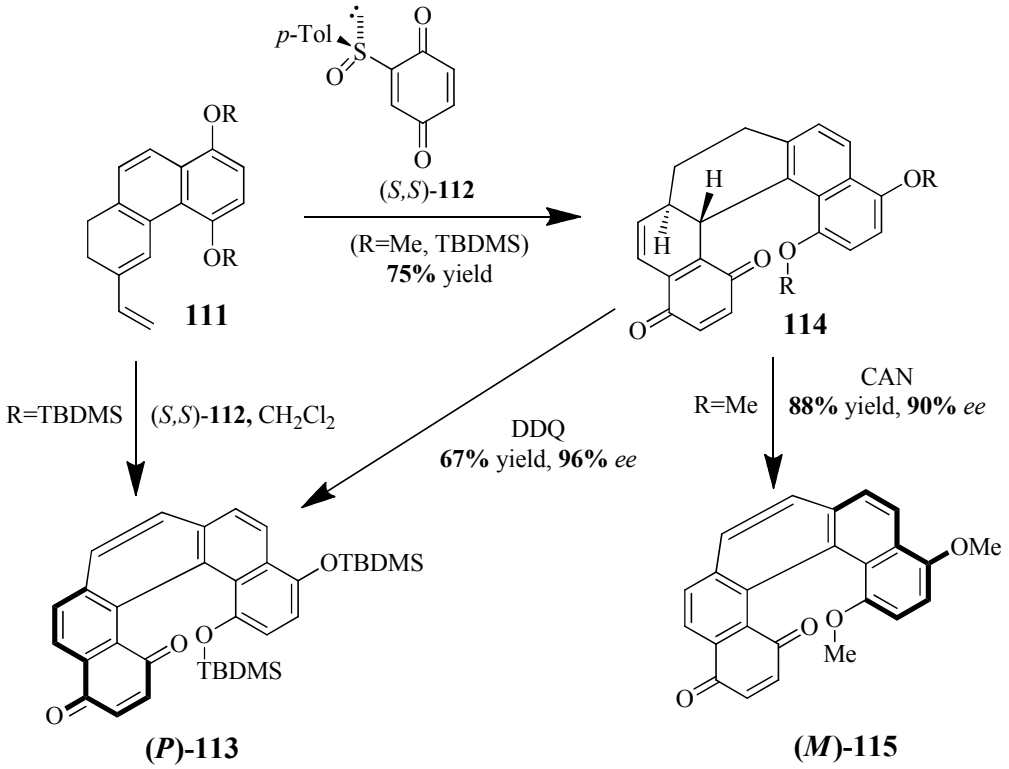
Scheme 1.32 Synthesis of novel oligothiophene (**110**)

1.4 ASYMMETRIC SYNTHESIS OF HELICENES

Another major challenge in helicene chemistry is the asymmetric synthesis of optically pure molecules with high enantioselectivity. Although synthesis of helicene molecules is difficult and optically pure, molecules synthesis through asymmetric way is more difficult task. Most of the asymmetric approaches reported were mainly based on the resolutions of the racemic derivatives using different chiral agents. Although several enantio- or diastereoselective syntheses have been reported in the literature, but only moderate asymmetric inductions have been achieved, except in a few cases. To extend the range of applications of functionalized helicenes, there is still a crying need for general, efficient and versatile enantioselective approaches to both ***M*** and ***P*** helimers.

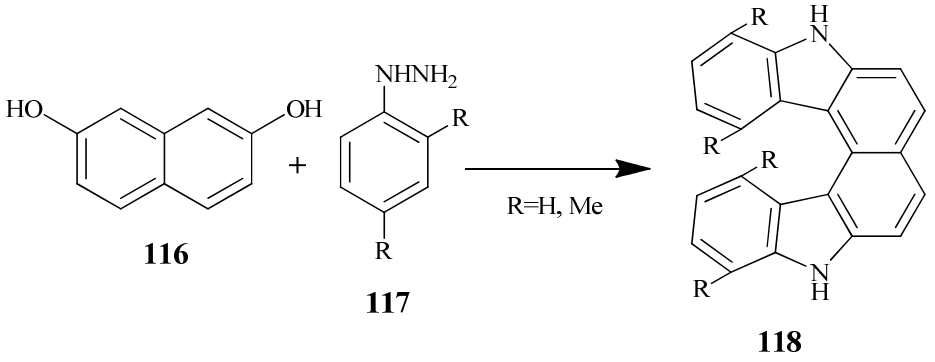
The first enantioselective synthesis of 7,8-dihydro[5]helicene quinones and bisquinones was done by Carreno and co-workers in 2001(Scheme 1.33). The reaction was done through a three-step one pot domino process of vinyl 3,4-dihydrophenanthrene **111** (R=TBDMS) with equivalents of enantiopure (*S,S*)-2-(*p*-tolylsulfinyl)-1,4-benzoquinone (**112**). Under very mild conditions, to 7,8-dihydro[5]helicene quinone (**114**) in 75% yield. Through a domino process

comprising a Diels-Alder reaction and the elimination of the sulfoxide, followed by aromatization of the ring of intermediate **114** (R=TBDMS) the optically pure helicene **113** was obtained with the absolute configuration ***P***. The aromatization of the ring of **114** (R=TBDMS) with DDQ gave helicene (*P*)-**113** in 67% yield with 96% *ee*, where as helicene (*M*)-**115** was obtained in 88% yield with 90% *ee* when the aromatization of **114** (R=Me) was effected with CAN (cerium ammonium nitrate).[47]



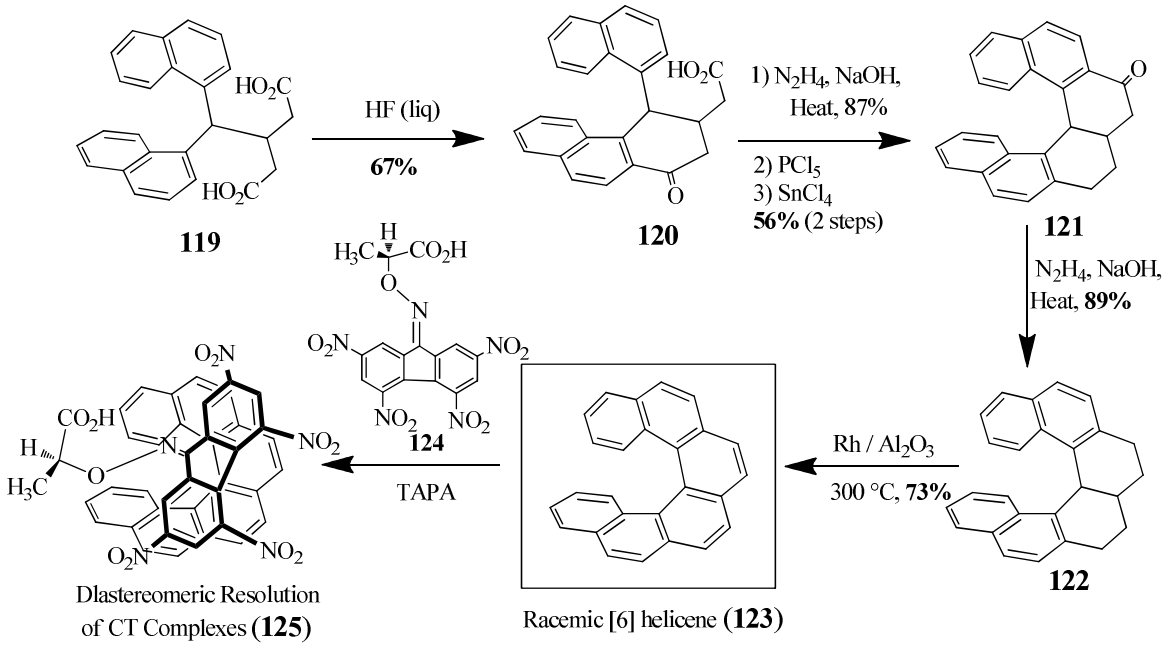
Scheme 1.33 Synthesis of optically pure bisquinones derivatives **113** and **115**

Before the early nineteenth century, only a few examples of aza[6]helicenes have been elaborated, and methods with general applicability for syntheses of such compounds are very rarely described. In 1927, Fuchs and Niszel first reported the pyrrolo[6]helicene **(118)** in racemic form via a non-photochemical approach (Scheme 1.34). Following the same preparative pathway, Pischel et al. described the synthesis of the corresponding tetramethyl derivative in a very poor yield and succeeded in separating its antipode using chiral HPLC.[48, 49]



Scheme 1.34 Synthesis of aza[6]helicenes and optical separation by chiral HPLC

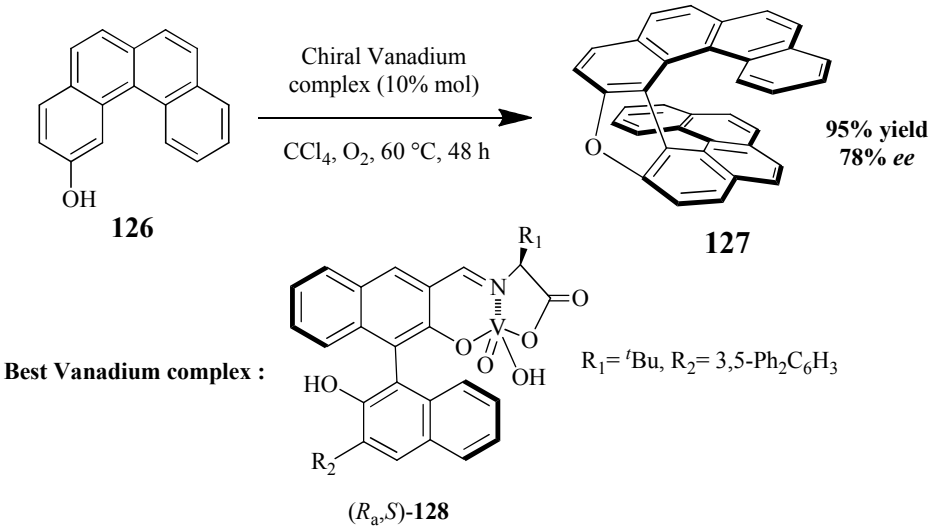
Another milestone in helicene chemistry was the first synthesis and the resolution of [6]helicene from Newman *et al.* in 1955 and in 1956 (Scheme 1.35). It definitively launched the chemistry of longer helicenes.[50, 51]



Scheme 1.35 Diastereomeric resolution of [6]helicene

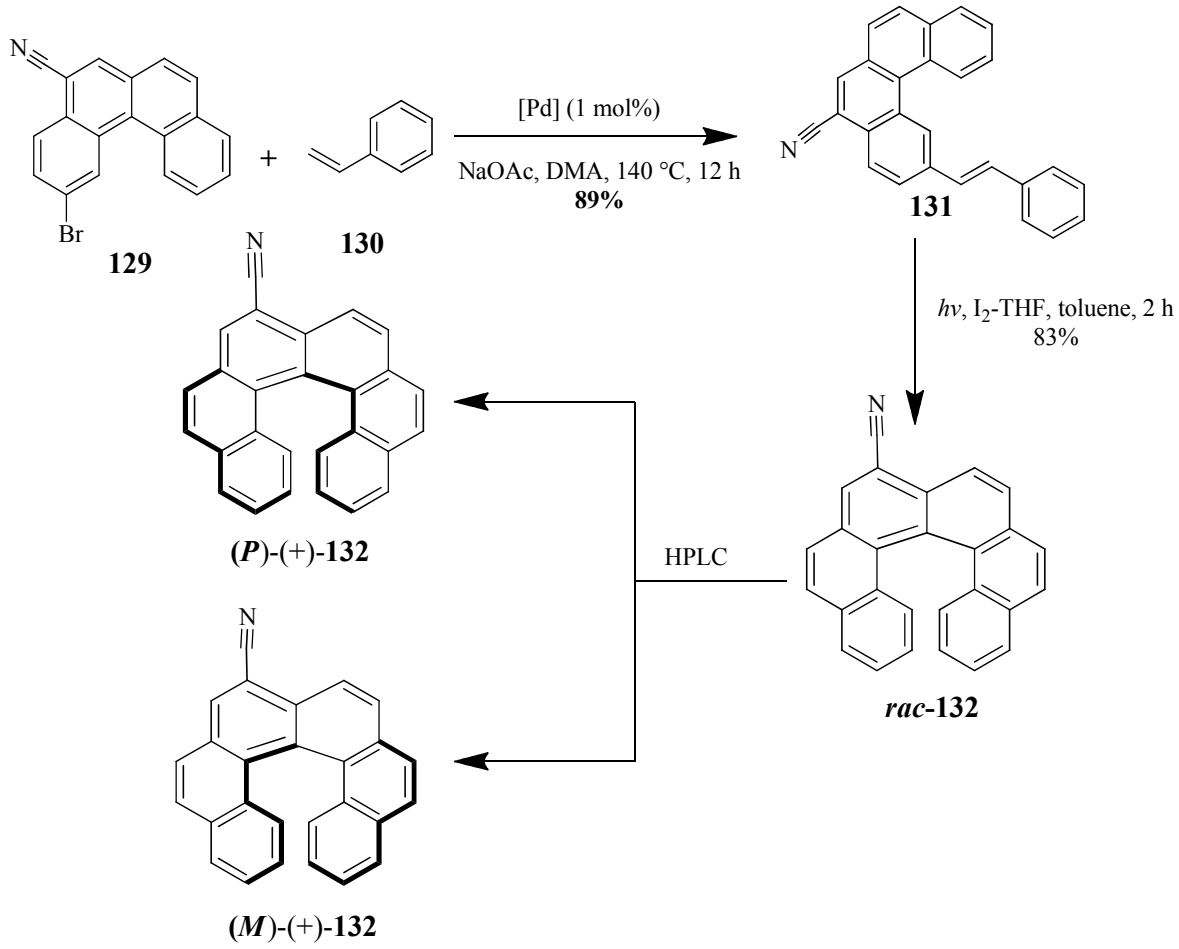
More recently, Hiroaki Sasai *et al.* developed a new way for the enantioselective synthesis of oxa[9]helicene (**127**) derivatives using different chiral vanadium complexes (Scheme 1.36).

They showed during the oxidative homocoupling reaction there is no diol and quinone was detected. They proved mononuclear binapthyl vanadium (V) complex (*R*a,*S*)-**128** where substituent attached at 3' position of the binapthyl unit is the more effective catalyst than other analogs (95% yield, 78% *ee*).[52]



Scheme 1.36 Asymmetric synthesis of oxa[9]helicene (**127**)

In 2016, B. B. Hassine *et al.* reported that they have successfully synthesized racemic 8-cyanohexahelicene (**132**), in a four step sequence with an overall yield of 58%, under mild conditions. The resolution of the racemic helically hexacyclic framework was successfully achieved to give the corresponding enantiomers in high enantiomeric purity (Scheme 1.37).[53]



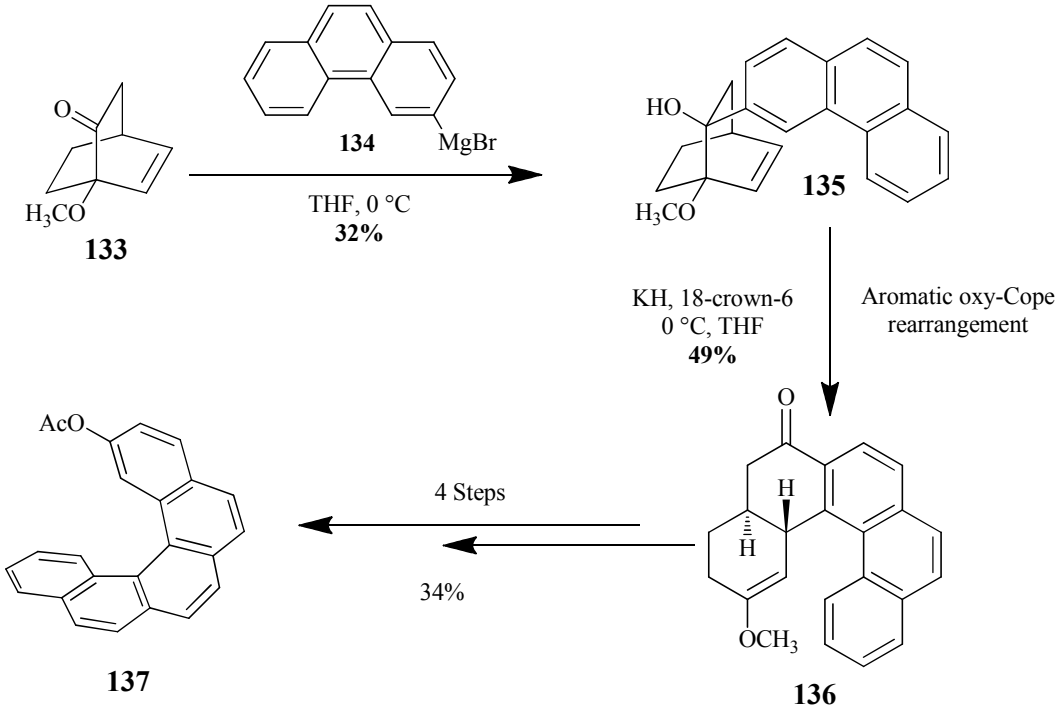
Scheme 1.37 Synthesis and optical resolution of 8- cyanohexahelicene (**132**)

1.5 PREVIOUS WORKS OF OUR GROUP

Our research group is working on helicene chemistry more than a decade. During this time, we have successfully shown different synthetic routes of the synthesis of carbohelicenes, helicene like molecules and oxa[9]helicene derivatives as well.

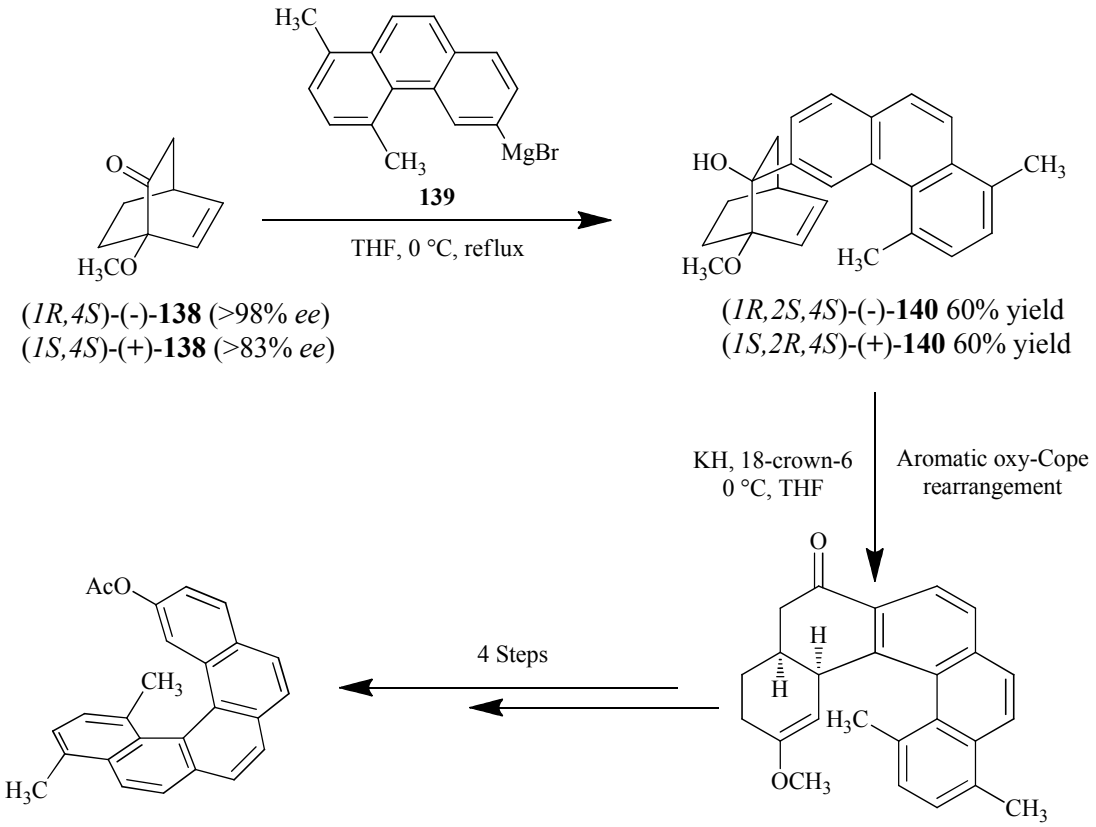
In 2002, we were described a new concept in the synthesis of functionalized carbohelicenes from two sequential accelerated anionic 3-oxy-Cope sigmatropic rearrangements for building up the carbon skeleton of [5] helicene. Some studies of the first rearrangement were previously reported in 1998 for making partly saturated or fully aromatic phenanthrenes. In this work toward [5]helicene derivatives, only one example was chosen with 3-

bromophenanthrene which was synthesized in six steps through anionic 3-oxy-Cope from bicyclo[2.2.2]ketone (**133**) and *p*-bromophenylmagnesium bromide (**134**) followed by the successive installation of the unsaturations in some rings in order to help in the final aromatization with DDQ (Scheme 1.38).[54, 55]



Scheme 1.38 Synthesis of a [5]helicene derivative (**137**) from an anionic 3-oxy-Cope rearrangement

In 2003, the continuation of our previous studies, we have auspiciously synthesized both enantiomers of 2-acetoxy-11, 14-dimethyl [5] helicene (**142**), using the same aromatic Oxy-Cope rearrangement strategy starting from the addition of 5,8-dimethylphenanthrenylmagnesium bromide (**139**) on resolved (*1R,4S*)-(-)- or (*1R,4S*)-(+)-l-methoxybicyclo- [2.2.2]oct-5-en-2-one (**138**). The outcome of this studies was outstanding because, at the end we obtained each enantiomer of **142** with excellent % ee. For (*P*)-(+)-**142**, it was >98% *ee* and for (*M*)-(-)-**142** >83% *ee* as well (Scheme 1.39).[56]



(*1R,4S*)-(-)-**138** (>98% *ee*)
(*1S,4S*)-(+)-**138** (>83% *ee*)

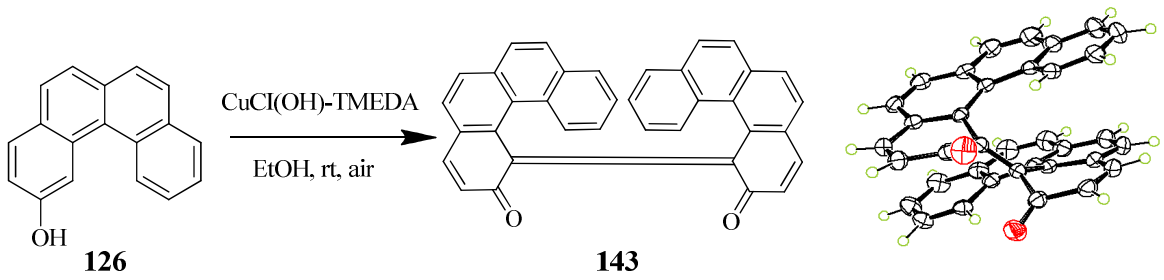
(*1R,2S,4S*)-(-)-**140** 60% yield
(*1S,2R,4S*)-(+)-**140** 60% yield

(4a*S,1*4d*R*)-(-)-**141** 47% yield
(4a*R,1*4d*S*)-(+)-**141** 35% yield

(*P*)-(+)-**142** (>98% *ee*) 24% yield
(*M*)-(-)-**142** (>83% *ee*) 34% yield

Scheme 1.39 Synthesis of optically pure 2-acetoxy-11, 14-dimethyl[5]helicene (**8**) enantiomers (***P*** and ***M***)

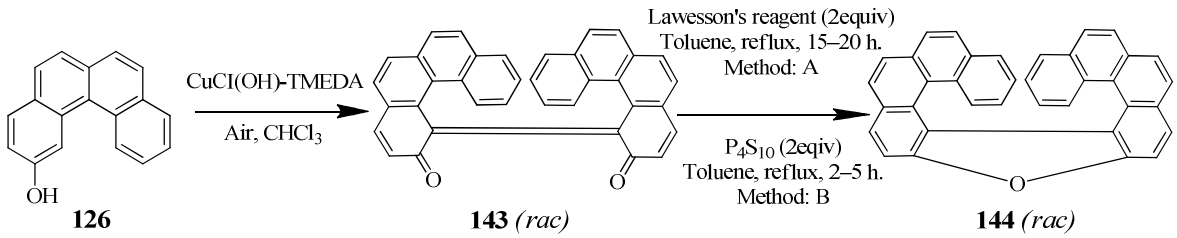
Our research group achieved another breakthrough in 2005, when we first synthesized quinone derivative (**143**) from 2-hydroxy benzo[c]phenanthrene (**126**) using oxidative coupling reaction. Previously, the quinone derivatives were described as the undesired by-product of the oxidative coupling reaction of phenols; but we have successfully synthesized and characterized the quinone derivative (**143**) with very good yield (82%). We have also figured out the exact molecular configuration of quinone derivative (**143**) by X-ray crystal analysis (scheme 1.40).[57]



126 **143**

Scheme 1.40 Synthesis of quinone (**143**) derivative from 2-hydroxy benzo[c]phenanthrene

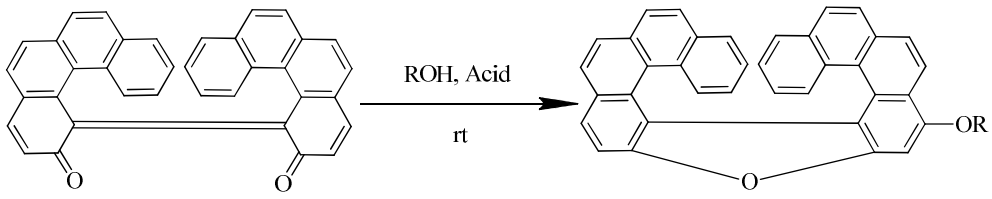
Few years later in 2011, M. Salim *et. al.* demonstrated a novel and efficient reductive cyclization of helical quinone mediated by Lawesson's reagents (LR) and P_4S_{10} that produces oxa[9]helicenes (Scheme 1.41).[58]



126 **143** *(rac)* **144** *(rac)*

Scheme 1.41 Synthesis of oxa[9]helicenes by LR or P_4S_{10}

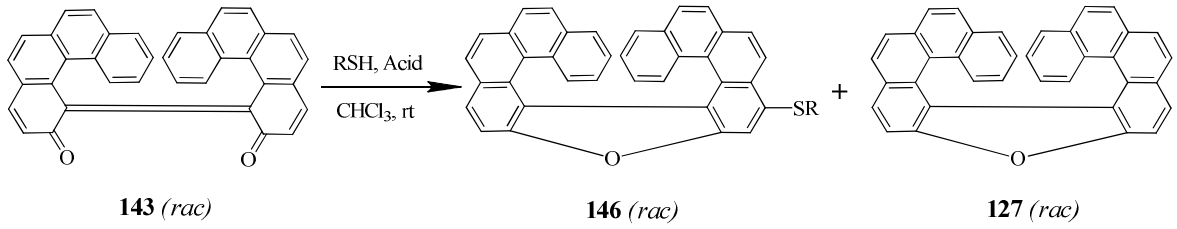
At the same year, M. Salim *et al.* have also demonstrated the novel and efficient synthetic method for producing 9-alkoxy-11-oxa[9]helicenes (Scheme1.42) from quinone derivative.[59]



143 *(rac)* **145** *(rac)*

Scheme 1.42 Synthesis of 9-alkoxy-11-oxa[9]helicenes (**145**)

As the continuation of M. Salim's previous work, he has also demonstrated the novel and efficient synthetic method for producing 9-thioalkoxy-11-oxa[9]helicenes (Scheme 1.43) from quinone derivative.[60]

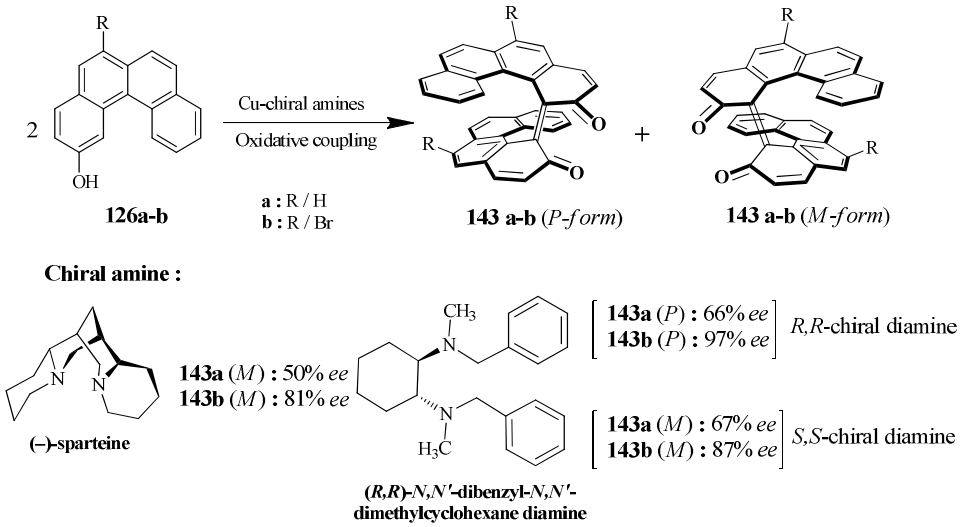


143 *(rac)* **146** *(rac)* **127** *(rac)*

Scheme 1.43 Synthesis of 9-thioalkoxy-11-oxa[9]helicenes (**146**)

Most recently, we have successfully asymmetrically synthesized quinone derivatives using different chiral mono- and diamines. In most cases, the desired products were either, not obtained or there was an enantiomeric excess of less than 5%. Only in the case of (–)-sparteine was the optically active quinone **143a** produced with over 40% *ee*. Because (–)-sparteine is a natural alkaloid, with only (–) - form being available in nature, only the *M*-form can be synthesized by this method. In order to obtain both enantiomers of **143a**, it is better to use artificially synthesized diamine ligands, which are available as both enantiomers. Therefore, we then attempted to use diazabicyclo[3.3.1]nonanes, which possess a framework in common with sparteine.

Treatment of copper chloride with newly synthesized chiral sparteine like diamine (*R* and *S* form) yielded both of enantiomers (*P*)-**143a** and (*M*)-**143a**, respectively, with moderate chemical yields and low enantioselectivities. With a view to further improving the enantioselectivity for the reaction, *N,N,N′,N′*- tetra substituted- 1,2-cyclohexane diamines were also investigated. In most cases, moderate to high chemical yields were obtained. In particular, excellent enantioselectivity (97% *ee*) was achieved for the reaction of **126b** with (*R,R*)-*N,N′*-dibenzyl-*N,N′*- dimethylcyclohexane diamine. The trend of the enantioselectivity of *N,N,N′,N′*-tetrasubstituted-1,2-cyclohexane diamines is also moderately good for **126a** (Scheme 1.44).[61]



Scheme 1.44 Asymmetric synthesis of quinone derivatives (**144a-b**)

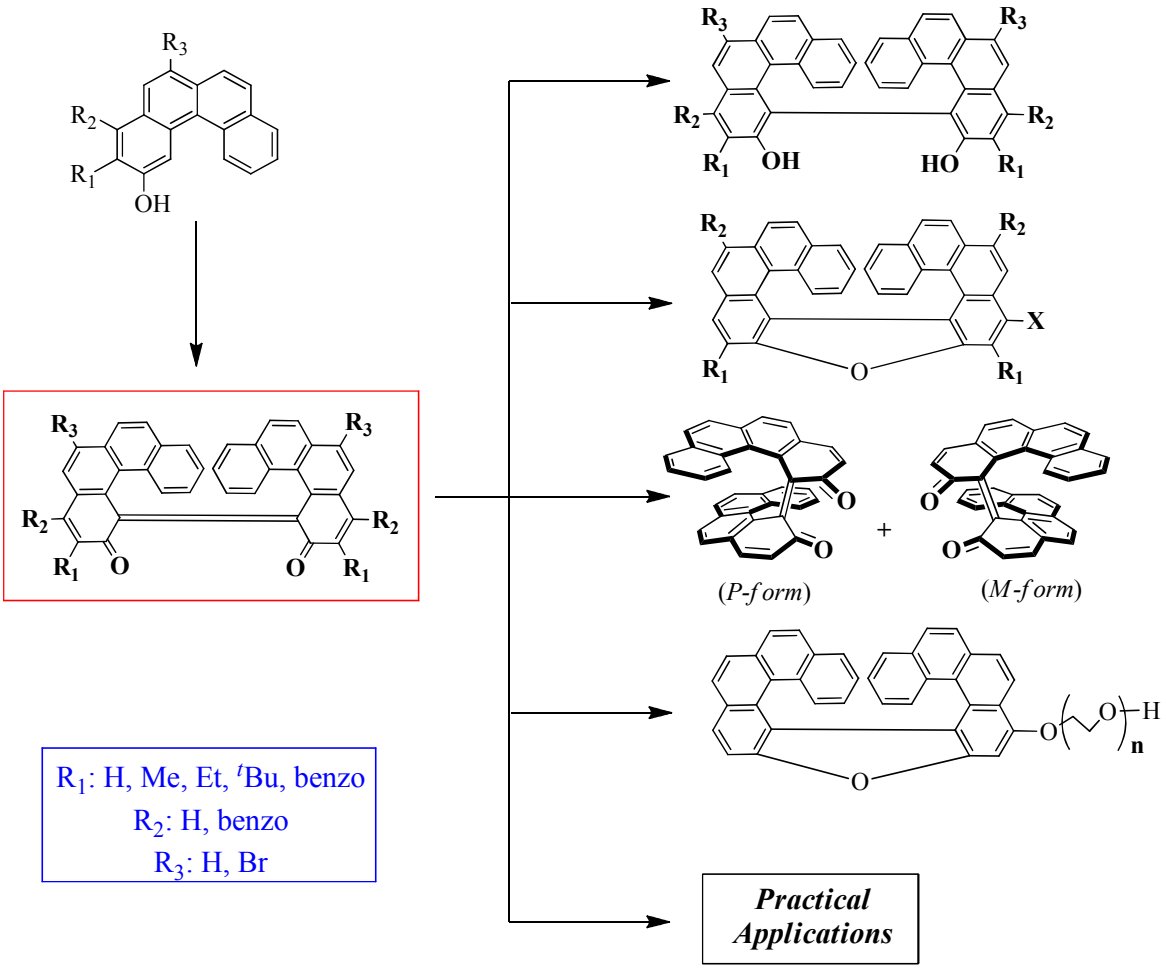
1.6 PURPOSE OF THE PRESENT RESEARCH WORK

According to the literature survey, it is clear that helicene chemistry is becoming one of the blooming branches of advance organic research. However, research on oxa[n]helicene derivatives and helical quinone type compounds are quite rare and a lot more interesting features are not revealed compare to other heterohelicene derivatives. Due to the multipurpose uses and interesting features of helicenes and helicene like molecules, this research is mainly focused on synthesis and characterization of optically pure function oxa[9]helicene and helicene like molecules through enantiomerically pure quinone derivatives. This thesis deals with different effective methods of the synthesis of oxa[9]helicene derivatives and at the very end, I will try to apply some of the amphiphilic oxa[9]helicene molecules on practical field. The main research goals are listed below:

- Synthesis of quinone derivatives from commercially available cheap starting materials.
- Reduced the quinone derivatives using available existing methods and use them as asymmetric catalysis like BINOL type compounds.
- Due to versatile applications of halogenated compounds in different coupling reactions, I will try to synthesis halogenated oxa[9]helicene derivatives from quinone derivatives.

- Literature survey shows that amphiphilic compounds have optical as well as electrical properties. So, I decided to synthesis amphiphilic oxa[9]helicene compounds with high optical purity.
- One of the major challenges in synthetic organic chemistry is synthesis of highly optically pure compounds. During this research I will also try to synthesis optically pure quinone derivatives either asymmetric synthetic method or through diastereomeric optically resolution technique.
- I am also very much interested to use some of my compounds in practical field as well.

The schematic presentation of my whole scientific research is shown in the following scheme 1.44.



Scheme 1.45 Graphical representation of research outline

1.7 REFERENCES

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CHAPTER 2

Synthesis of helical quinone derivatives by oxidative coupling of substituted 2-hydroxybenzo[c]phenanthrenes

Synopsis

I have developed a concise synthesis method of novel substituted quinone derivatives from commercially available starting materials. For this synthesis, I utilized classical photo-induced 6π-electro cyclization followed by oxidative aromatization reaction and subsequent oxidative coupling reactions in the presence of CuCl(OH)-TMEDA. The unique quinone derivatives were characterized by IR, ^{1}H and ^{13}C NMR spectroscopies, HRMS and X-ray data analysis. In some cases, the keto-dimers were obtained as significant intermediates for the quinone synthesis.

CHAPTER 2

2.1 INTRODUCTION

Oxidative phenol coupling reactions are well-known methods utilized in organic chemistry for the synthesis of biaryl compounds.[1] Due to a favorable one-electron oxidation utilizing a mild oxidant such as copper salts, these transformations can be performed under moderate reaction conditions that tolerate many functional groups. It is interesting to note that oxidative phenol coupling reactions have many applications in asymmetric synthesis.[1c,2] This versatility distinguishes the oxidative coupling from other biaryl synthetic methods such as the Scholl reaction[3] and the Ullman type reactions.[4]

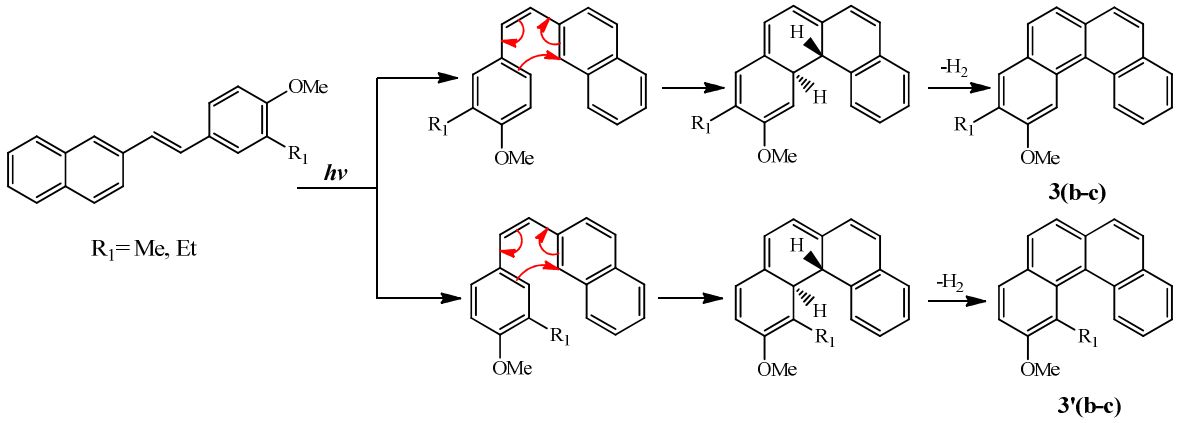
The conversion of phenols into bi-phenol derivatives has been utilized for the synthesis of many important natural compounds[5] and chiral ligands such as BINOL and its related derivatives.[2] On the other hand, the oxidative coupling reactions of phenols also generate quinone derivatives, which are formed by further oxidation of bi-phenol derivatives. The quinone derivatives have long been regarded as an undesired byproduct of the oxidative coupling reaction of phenols.[6] Considerable attention has been focused on the study and application of bi-phenol derivatives. However, the investigation of the corresponding quinone derivatives is limited. In particular, the 2,2'-diphenoquinone derivatives which are synthesized by the oxidation of 2,2'-biphenols,[7] are less studied compared to the 4,4'-diphenoquinone derivatives.[6] Previously, our research group has reported the synthesis of a helical shaped quinone derivative which was synthesized by oxidative coupling of 2-hydroxybenzo[*c*]phenanthrene.[8] Most recently, we have also reported the asymmetric synthesis of helical quinone derivatives by using chiral diamine-copper complexes.[9] The structure of the helical quinone derivative is discriminated by its strained polycyclic benzene rings. Thus, we have described the applications of the helical quinone derivatives.[10]A novel synthesis of oxa[9]helicenes utilizing the reaction of helical quinones with Lawesson's reagent,[11] phosphorus pentasulfide,[11]aliphatic alcohols[12] and thiols[13] has also been reported by our research group. Despite the major advances that we have made for the synthesis of oxa[9]helicene derivatives from quinone, we were eager to investigate whether it would be possible to identify a new route for the synthesis of substituted quinone derivatives.

In this chapter, I have described a short-step synthesis of helical quinone derivatives from simple starting materials that are commercially available and easily accessible after a few simple synthetic steps (e.g. Siegrist reaction[14] and photocyclization[15]).

2.2 RESULTS AND DISCUSSION

The starting materials, methoxy-substituted imine derivatives **1a-f** were obtained from the condensation of aniline and the corresponding aldehydes, which are commercially available. The Siegrist reaction was utilized to produce the stilbene derivatives **2a-d** and **2f** by the condensation of 2-methylnaphthalene in DMF.[14] Based on ^{1}H NMR spectra, the exact geometric isomer (*Z/E*) of the stilbene derivatives **2a-d** and **2f** were confirmed (Table 2.3). In all cases, the proton at C-11 and C-12 shows two-doublet peak at around 7.13-7.21ppm and the coupling constants are around 15-16 Hz. This indicated that, the protons at C-11 and C-12 position are in anti position. Meanwhile, in case of vicinal *cis*-protons, the coupling constant should be around 10 Hz. Without any doubt, we can say that, the newly formed **2a-d** and **2f** derivatives have *E*-stereochemistry at the double bond.

The 2-methoxybenzo[*c*]phenanthrene derivatives **3a-e** and the 8-hydroxybenzo[*c*]chrysene derivative **3f** were obtained by photocyclization using a 450 W high-pressure mercury lamp in cyclohexane (Table 2.4). These reactions were performed with a stoichiometric amount of iodine as an oxidizing agent and an excess amount of propylene oxide (5-35 ml).[15] The photolysis was performed on a scale of 2-10 mmol per run, in a 1.4 L reactor for approximately7-8 h. This provided fair to very good yields of the 2-methoxybenzo[*c*]phenanthrene derivatives **3a-d** and the 8-methoxybenzo[*c*]chrysene derivative **3f**. However, in both cases of **2b** and **2c**, mixtures of two regioisomers (**3b** and **3b'**, **3c** and **3c'**) were obtained in the ratio ca. 7:3, respectively (Scheme 2.1).



Scheme 2.1 Photocyclization process of **2b** and **2c** (*E*)-stilbene derivatives and formation of regioisomers **3b'** and **3c'**

Furthermore, in the case of **2d**, only one isomer of **3d** was obtained. This was likely due to the presence of the bulky *t*-butyl group, which may prevent the formation of the corresponding regioisomer. These mixtures (**3b** and **3b'**, **3c** and **3c'**) were utilized for the next demethylation reaction without further purification.

The bromo-substituted methoxy derivatives **3e** and **3g** were brominated using pyridinium tribromide as a brominating reagent in chloroform. The reaction occurred regioselectively at the 6-position of **3a** and the 14-position of **3f**.

The demethylation of **3a-g** using method A or method B led to the 2-hydroxybenzo[*c*]phenanthrene derivatives **4a-g** with very good yields (Table 2.5). Lastly, the 2-hydroxy benzo[*c*]phenanthrene derivatives were utilized in the oxidative coupling reaction with CuCl(OH)-TMEDA[16] in EtOH to produce **5a-g** with very good to excellent yields (Table 2.6).

A possible oxidative coupling reaction mechanism (Scheme 2.2) shows that the reaction proceeded regioselectively at the 1-position of the 2-hydroxybenzo[*c*]phenanthrene derivatives **4a-g**. In these reactions, keto dimers may be formed as an intermediate for all of the **5a-g** derivatives. However, the ^{1}H NMR spectra of **5a–e** revealed no distinct keto-dimer peaks. This may indicate that, the intermediate keto-dimers might be highly unstable, becoming further oxidized to convert to the more stable quinone form. Nevertheless, in the cases of **5f** and **5g**, the keto-dimers were obtained as a stereo-isomeric mixture (*meso*-form

and (*R*, R**)-form). The extra stability of the keto-dimer of **5f'–g'** might be due to the benzo fused ring at R^1 and R^2 position. After some work out at different reaction conditions we have successfully obtained enriched *meso*-isomer of **5f'**. However, time course ^{1}H NMR spectra analysis revealed that, the *meso*-isomer was isomerized in $CDCl_3$ at room temperature into (*R*,R**)-isomer with in a period of time (Figure 2.1). In case of **5f'**, the methine protons of *meso*-isomer was observed at 5.80 ppm. On the other hand, (*R*, R**)-isomer shows the corresponding protons at 5.64 ppm. This phenomenon suggested the existing equilibrium between two keto-dimers.

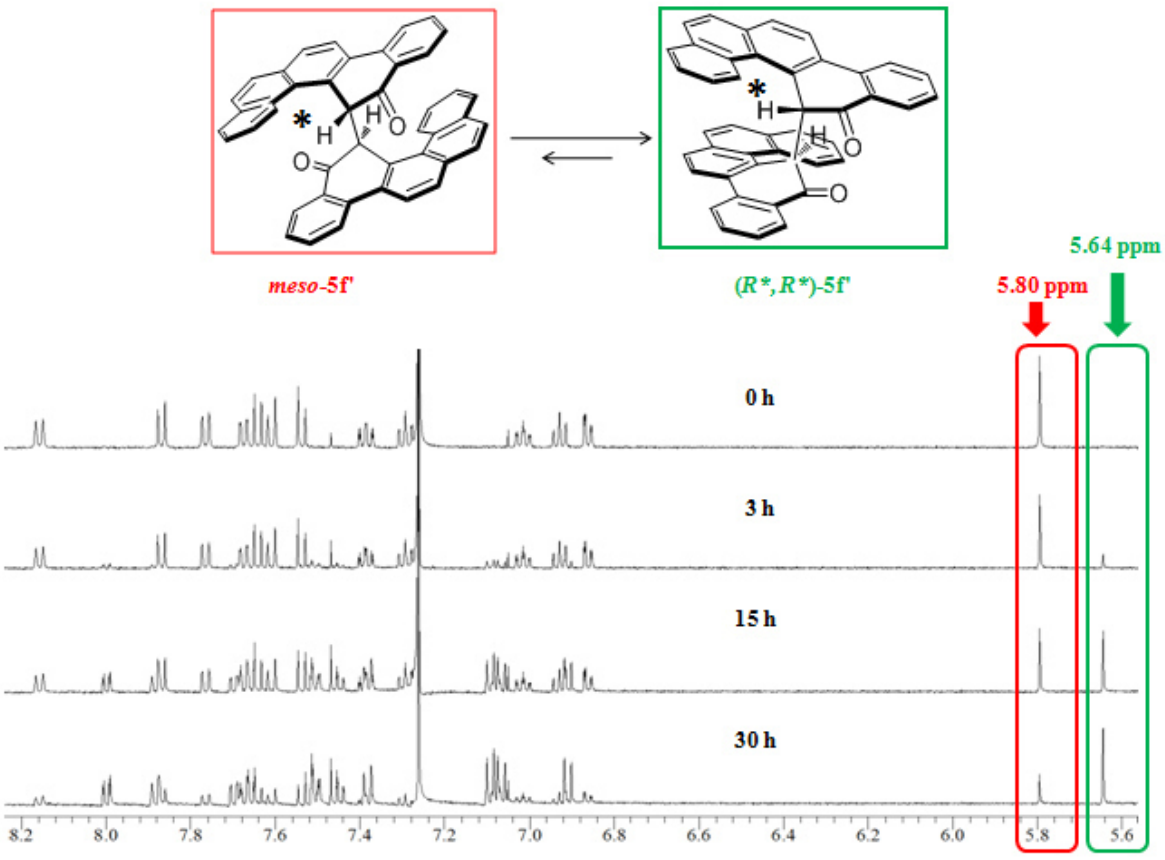
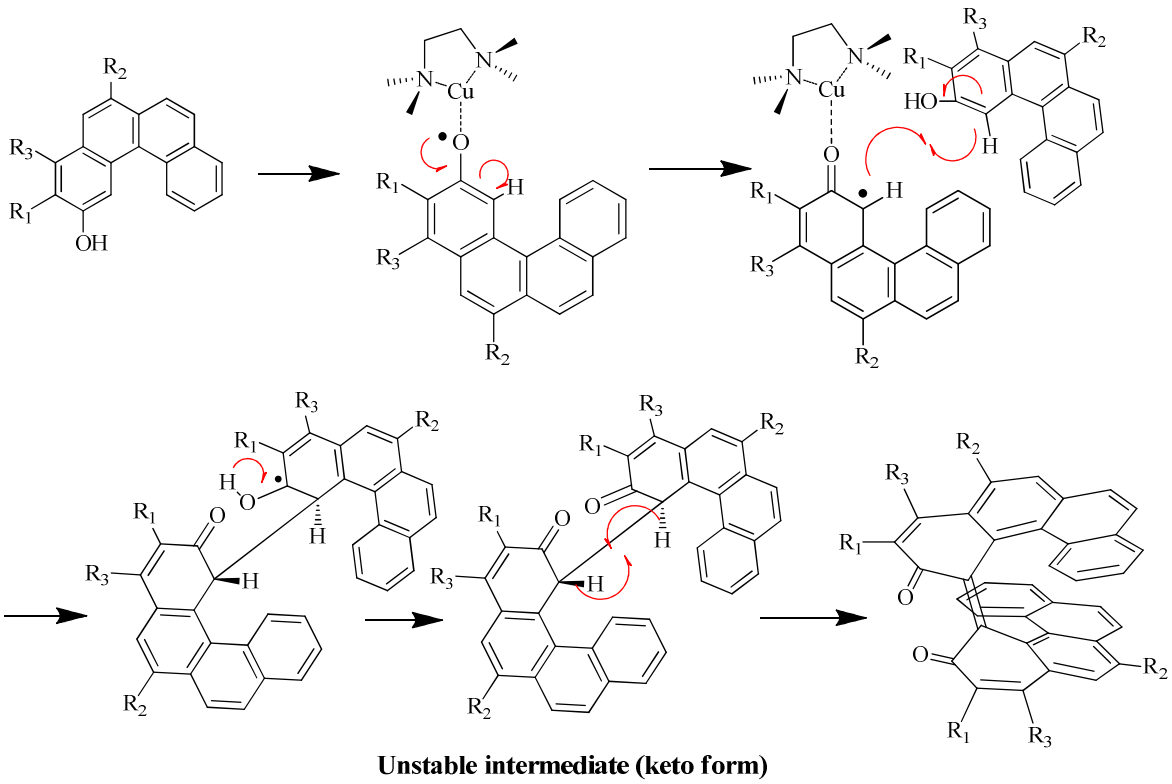


Figure 2.1 Time course ^{1}H NMR spectra of meso-**5f'** and (*R**, *R**)-**5f'** in $CDCl_3$ at room temperature

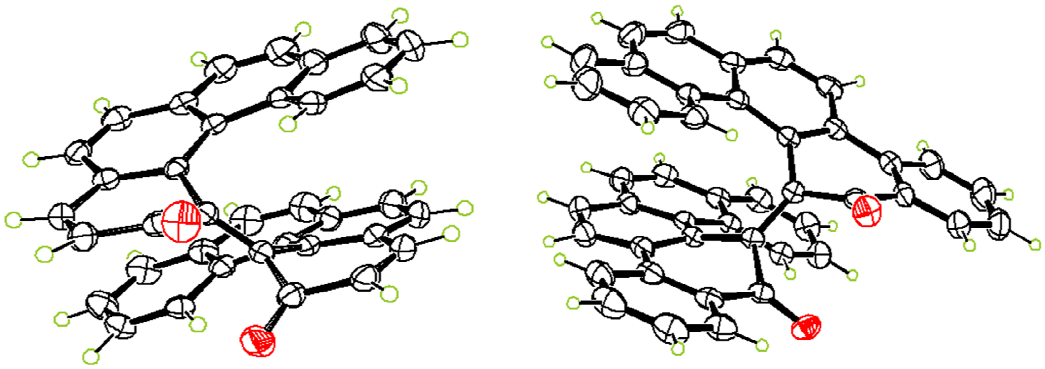
However, the underlying mechanism of quinone synthesis remains elusive. Our current research is focused on understanding this mechanism.



Scheme 2.2 One of the possible oxidative coupling reaction mechanism of benzo[c]phenanthrene derivatives using CuCl(OH)-TMEDA complex

After further manipulation of the reactions by refluxing with toluene the ketodimers **5f'** and **5g'** were converted to quinones **5f** and **5g**.

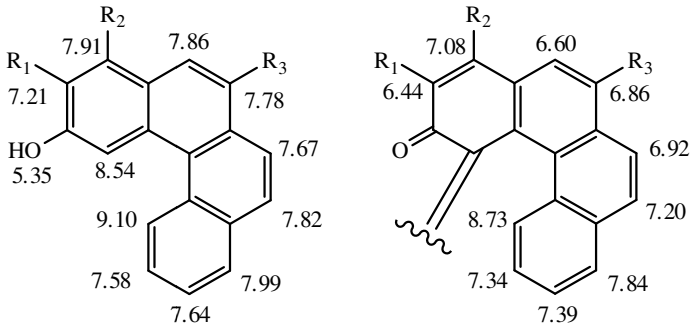
A single crystal of **5a** obtained from the ethanol solution and **5f** obtained from the chloroform solution were subjected to X-ray crystal analysis. The crystal structure revealed that the fully eclipsed helical structure of **5a** and **5f** consisted of a symmetrical moiety connected by a *Z*-configured double bond (Figure 2.2).[8]



5a **5f**

Figure 2.2 The *Z*-configuration of **5a** and **5f** were confirmed by X-ray diffraction (Side view) analysis with ellipsoids at 35% probability

The ^{1}H NMR spectrum supported the structure determined by X-ray analysis. Indeed, all of the signals in the ^{1}H NMR spectrum of **5a-g** in $CDCl_3$ were assigned on the basis of chemical shifts and coupling constants. Significantly, these signals shifted upfield (ca. $\Delta\delta$ = 0.24–1.26 ppm) compared to **4a-g** (Figure 2.3).



4a $R_1=R_2=R_3=H$ **5a**

Figure 2.3 The ^{1}H NMR chemical shift (δ/ppm) data of **4a** and **5a** in $CDCl_3$

The comparative ^{1}H NMR spectra of **5a-e** shows that, the signal for H-4 appeared more up field when different functional group attached at H-3 position. The reason behind the trend was while the functional group became bigger and bigger the (e.g. ^{t}Bu > Et > Me > H) proton

at C-4 position fees more shielding effect. However, in case of **5e** where a bromine atom attached at C-8 position the signal of H-4 appeared more down field due to deshielding effect (Figure 2.4).

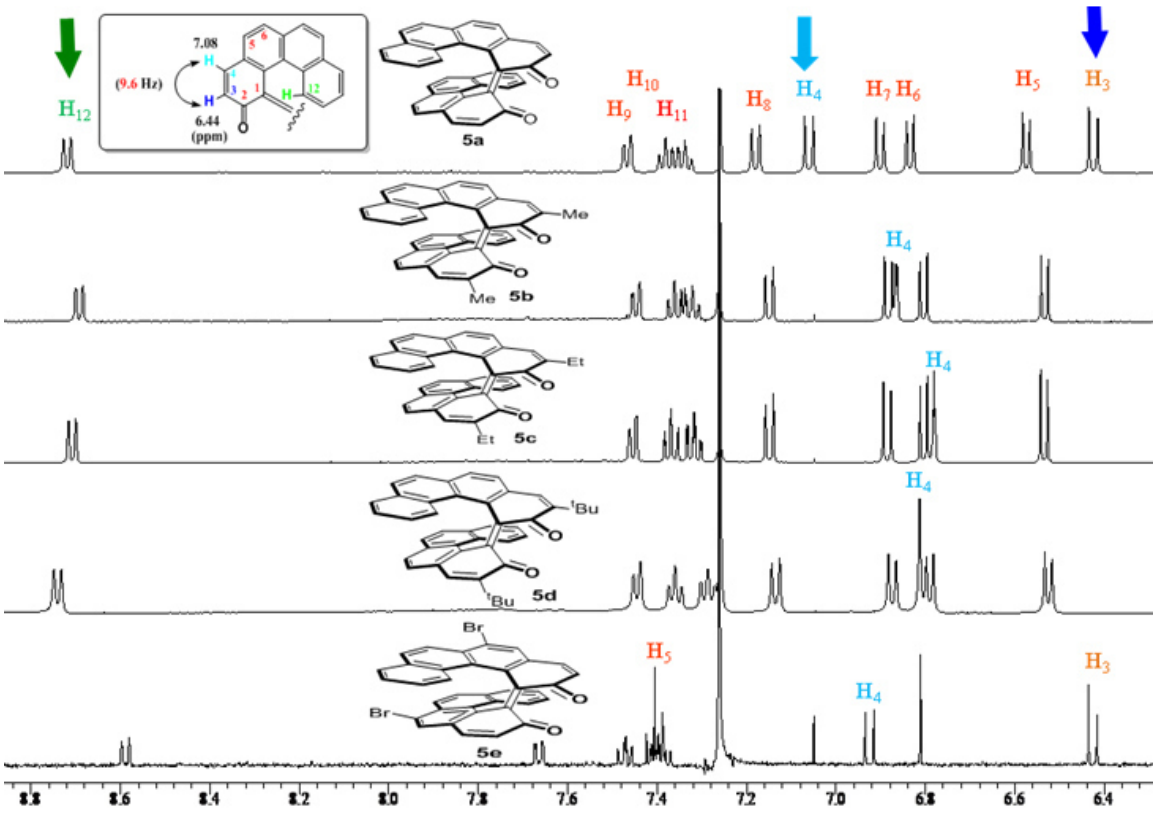


Figure 2.4 Comparative ^{1}H NMR spectra of quinone derivatives

Single-crystal X-ray analysis of **5a** and **5f** established the structure of the compounds. The compounds were crystallized in the triclinic *P1* space group; their unit cell consists of two molecules one is "*P*" conformation and the other in "*M*" conformation. This indicates the absence of any other spontaneous resolution, a phenomenon occasionally observed in some helical molecules during crystallization.[17] Crystal structure is packed in alternative *P* and *M* along each channel (Figure 2.5). The consecutive molecules of **5a** are connected by π-staking (C3-C42, 3.541 Å; C6-C39, 3.540 Å; O2-C67, 3.549 Å; O2-C68, 3.479 Å; O4-C32, 3.478 Å; O4-C31, 3.55t Å). In case of **5f** the torsion angles (except C3-C2-C24-C25 is -9.2°) are positive sign that means, two benzo fused chrysene moiety in **5f** are oriented in clockwise direction. The clockwise rotation of the rings occurred due to the carbonyl group at C1 and

C23 position. These carbonyl groups exert much steric strain to the chrysene moiety and made double layer like shape of the molecules. This positive value also defines that, the crystal data are for *P* isomer of **5f** compound.

Table 2.1 Selective dihedral angle (°) of **5f**

C-C bonds	Dihedral angle (°)
C6–C5–C4–C3	16.3
C5–C4–C3–C2	21.3
C4–C3–C2–C24	50.8
C3–C2–C24–C25	**-9.2**
C2–C24–C25–C26	51.4
C24–C25–C26–C27	18.7
C25–C26–C27–C28	16.6

Table 2.2 Selective dihedral angle (°) of **5a**

C-C bonds	Dihedral angle (°)
C15–C16–C17–C18	-15.9
C16–C17–C18–C1	-20.8
C17–C18–C1–C19	-52.9
C18–C1–C19–C36	**13.1**
C1–C19–C36–C35	-51.7
C19–C36–C35–C34	-21.5
C36–C35–C34–C33	-12.1

The other torsion angles of **5f** among the inner carbon atoms were found as the Table 2.1 and the summation of the seven dihedral angles (C6–C5–C4–C3, C5–C4–C3–C2, C4–C3–C2–C24, C3–C2–C24–C25, C2–C24–C25–C26, C24–C25–C26–C27, C25–C26–C27–C28) is 165.9°, which is significantly much larger than those of literature values (e.g. for carbonyl linked 1,1'-bitriphenylene is 90.7 ° and for 3,3-biphenanthrene based sila[7]helicene is 99.5°).[18] The large torsion angle value suggesting different degrees of distortion in the aromatic rings. Because of torsion strain generated due to the helical shape. The bond length in the skeleton is also different. In comparison of the standard bond length of benzene (1.39 Å),[19]

the range of C-C bond lengths of the inner helix was observed 1.410-1.487 Å, while the same on the outer periphery was shorter, as seen in the range of 1.357-1.367 Å. Another interesting feature of helical compound is the inter planar angel.

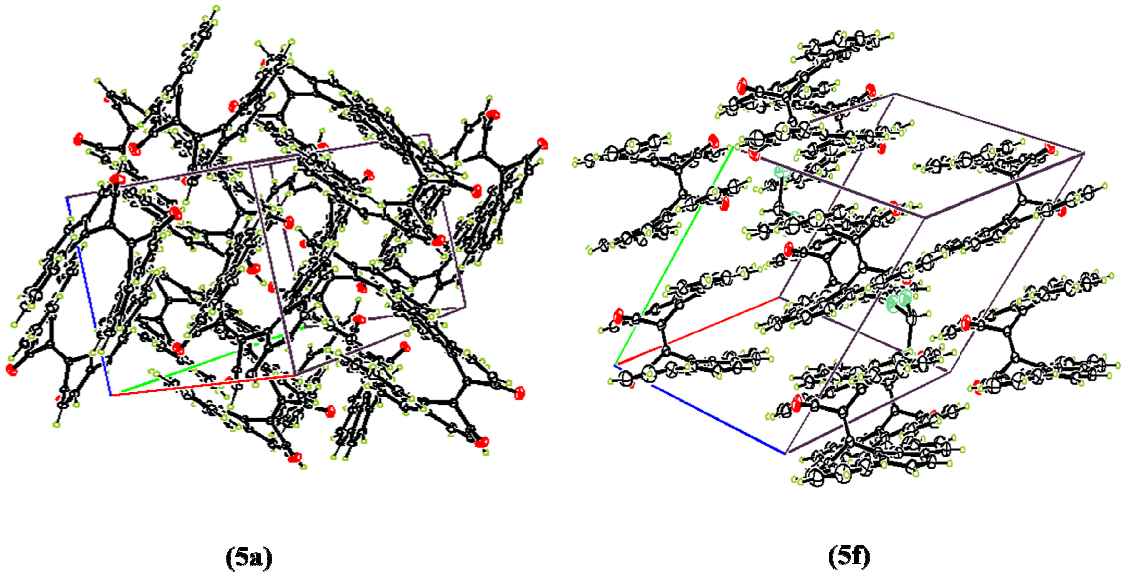


Figure 2.5 Unit cells of **5a** and **5f** with ellipsoids at 30% probability

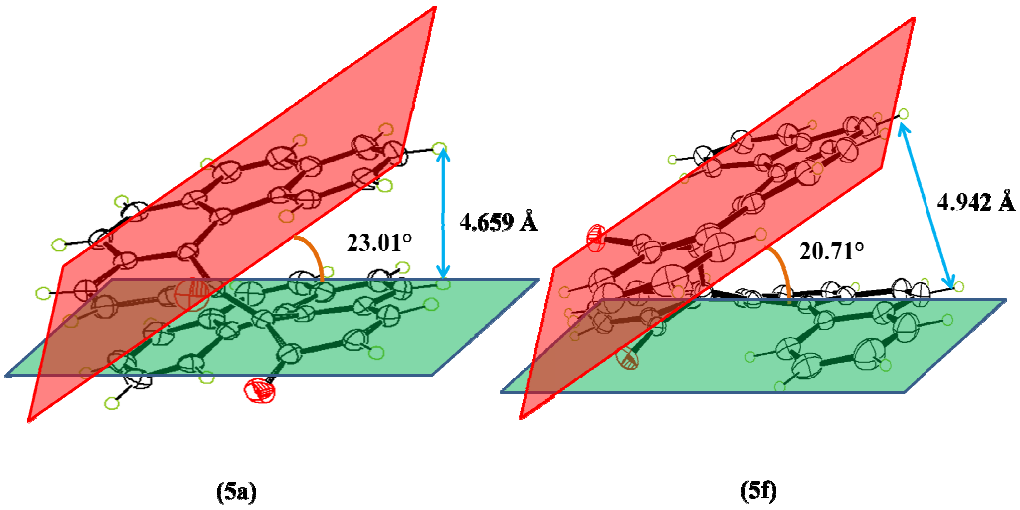


Figure 2.6 Inter planar distance and angle of **5a** and **5f**

For **5f**, it was found as 20.71° (Figure 2.6) and the value agree well with the known observation for large helicenes where it tends to decrease for elongated structure.[20] The same circumstances are also true for **5a**. In Table 7, dihedral angles of inner carbon atoms are

enlisted and the summation of the angles is found 161.8º. Except the dihedral angle of C18–C1–C19–C36 is positive sign compare to other inner carbon atoms. The benzo [c] phenanthrene moiety are oriented in anti-clockwise direction and the dihedral angles in Table 2.2 are for *M* isomer of **5a**.

2.3 EXPERIMENTAL PROCEDURE

2.3.1 Materials and Methods

All reagents were prepared using chemicals obtained from commercial sources and used without further purification. Most of the reactions were performed under aerobic or anaerobic conditions in oven-dried glassware with magnetic stirring. All reactions were monitored by analytical thin layer chromatography (TLC) using Merck pre-coated silica gel glass plates (0.25mm) and spot detected under either I_2 chamber or UV-lamp. The flash column chromatography was carried out over silica gel 60 (230–400 mesh), purchased from Kanto Chemical Co. Inc. Melting points were determined on a Yanagimoto melting point apparatus.

FT-IR spectra were recorded on a JASCO FTIR spectrometer 4200; and samples were prepared as KBr (Sigma Aldrich, USA) plates. NMR spectra were recorded in $CDCl_3$ (Kanto Chemical Co. Inc.) at Varian NMR System 500 (Varian LTD) at 500 MHz for ^{1}H NMR and 125 MHz for ^{13}C NMR as well. The internal standard for NMR was 0.03% tetramethylsilane (TMS). Chemical shifts (δ) are given in ppm respect to TMS and coupling constants (*J*) are given in Hz. High-resolution mass spectra (HRMS) were acquired on a JMS-700AM (JEOL) and JSM-777V (JEOL) spectrometer using EI (Electron Impact) and FAB (Fast Atom Bombardement) techniques.

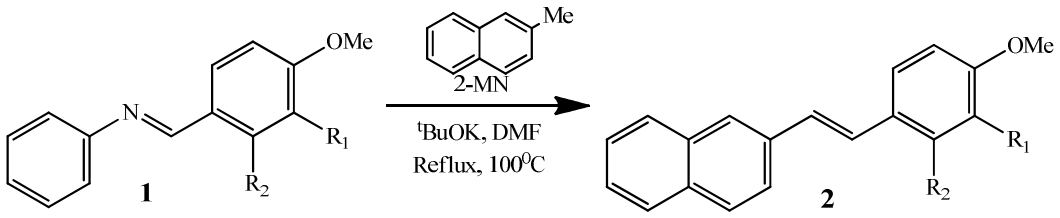
X-ray diffraction of the single crystals were recorded using CrystalClear (Rigaku/MSC, 2006), CrystalClear, SHELXS2013/1 (Sheldrick, 2008), SHELXL2014/7 (Sheldrick, 2008), Mercury (Macrae et al., 2006), SHELXL2014/7 computer programs.

2.3.2 General Experimental Procedure

2.3.2.1 Siegrist Reaction: General Procedure for the Preparation of 2-[2-(4-Methoxyphenyl)vinyl]naphthalene Derivatives (2a-d and 2f).

1a (4.22g, 20 mmol), 2-methyl naphthalene (2.84g, 20mmol) and ^{t}BuOK (2.69 g, 24 mmol)were combined with anhydrous DMF (20ml) and the mixture was refluxed at 100°C for approximately 4h. Next, the product was washed with 6N HCl and methanol. Eventually, we obtained the pale yellow crystal of **2a** with a 95% yield and an Mp=173-176°C.

Table 2.3 Synthesis of (*E*)-Stilbene derivatives from different Aza stilbene precursor (**Siegrist reaction**)



Entry[b]	Substrate/R_1, R_2	Reaction Condition **1** : 2-MN : ^{t}BuOK	Time/h	**2** (Yield%)[b]
1	**1a:** R_1, R_2/H		4	**2a** (95)
2	**1b:** R_1/Me, R_2/H		14	**2b** (29)
3	**1c:** R_1/Et, R_2/H	1 : 1 : 1.1	18	**2c** (82)
4	**1d:** R_1/^{t}Bu, R_2/H		23	**2d** (43)
5	**1f:** R_1,R_2/Benzo		3	**2f** (68)

[a] Isolated yield.
[b]All reactions were carried out in anhydrous DMF

2.3.2.1.1. *2-[2-(4-Methoxyphenyl)vinyl]naphthalene (**2a**):* Pale yellow crystal, Mp=173–176°C. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=3.84 (3H, s), 6.92 (2H, d, *J*=6.5 Hz), 7.14 (1H, d, *J*=16.5 Hz), 7.18 (1H, d, *J*=16.5 Hz), 7.42-7.49 (4H, m), 7.72 (1H, dd, *J*=8.5, 1.5 Hz), 7.79-7.82 (4H, m) ppm;^{13}C NMR ($CDCl_3$, 125 MHz): δ=55.58, 114.41, 114.43, 123.69, 125.92, 126.35, 126.51, 126.91, 127.91, 127.99, 128.00, 128.13, 128.47, 128.79, 130.40, 133.08, 133.99, 135.38, 159.59 ppm; HRMS (EI) calcd for $C_{19}H_{16}O$ $[M]^+$: 260.1201, found 260.1202.

2.3.2.1.2. *2-[2-(3-Methyl-4-methoxyphenyl)vinyl]naphthalene (**2b**):* Colorless solid, Mp=142–145°C. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=2.24 (3H, s, -Me), 3.85 (3H, s, -OMe), 6.84

(1H, d, *J*=8.0 Hz), 7.13 (1H, d, *J* =16.0 Hz), 7.18 (1H, d, *J*=16.0 Hz), 7.34 (1H, d, *J*=8.5 Hz), 7.39 (1H, s), 7.43 (1H, t, *J*=6.5 Hz), 7.47 (1H, t, *J*=6.5 Hz), 7.73 (1H, d, *J*=9.0 Hz), 7.79-7.83 (4H, m) ppm;^{13}C NMR ($CDCl_3$, 125MHz): 16.60, 55.65, 110.28, 123.72, 125.74, 125.85, 126.25, 126.48, 126.59, 127.13, 127.91, 128.12, 128.44, 128.84, 129.03, 129.89, 133.04, 134.02, 135.53, 157.91 ppm; HRMS (EI) calcd for $C_{20}H_{18}O$ $[M]^+$: 274.1357, found 274.1363.

2.3.2.1.3. *2-[2-(3-Ethyl-4-methoxyphenyl)vinyl]naphthalene (**2c**):* White crystal, Mp=105–108°C. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=1.24 (3H, t, *J*=7.5 Hz), 2.68 (2H, q, *J*=7.5 Hz), 3.88 (3H, s, -OMe), 6.84 (1H, d, *J*=8.0 Hz), 7.17 (1H, d, *J*=16.0 Hz), 7.19 (1H, d, *J*=16.0 Hz), 7.31 (1H, t, *J*=8.5 Hz), 7.36 (1H, d, *J*=8.0 Hz), 7.36-7.40 (3H, m), 7.61 (1H, s), 7.70-7.82 (3H, m) ppm;^{13}C NMR ($CDCl_3$, 125MHz): 14.18, 23.38, 55.42, 110.30, 123.48, 125.41, 125.61, 126.01, 126.24, 126.31, 127.01, 127.67, 127.88, 128.20, 128.92, 129.76, 132.79, 132.88, 133.77, 135.30, 157.30 ppm; HRMS (EI) calcd for $C_{21}H_{20}O$ $[M]^+$: 288.1514, found 288.1517.

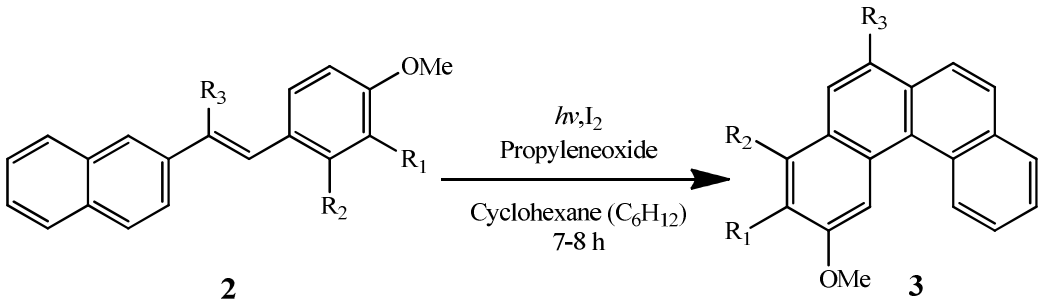
2.3.2.1.4.*2-[2-(3-tert-Butyl-4-methoxyphenyl)vinyl]naphthalene (**2d**):* White needle-like crystal, Mp=128–132ºC. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=1.43 (9H, s, $(-CH_3)_3$), 3.87 (3H, s, -OMe), 6.89 (1H, d, *J*=8.5 Hz), 7.12 (1H, d, *J*=16.5 Hz), 7.20 (1H, d, *J*=16.5 Hz),7.39-7.47 (4H,m), 7.49 (1H,s), 7.73 (1H, dd, *J*=8.5 Hz), 7.80 (1H, d, *J*=8.5 Hz), 7.81 (1H, d, *J*=7.5 Hz), 7.83 (1H,s) ppm;^{13}C NMR ($CDCl_3$, 125 MHz): δ=29.69, 34.91, 55.15, 111.76, 123.50, 125.17, 125.18, 125.59, 125.99, 126.24, 127.67, 127.87, 128.19, 129.27, 129.44, 132.78, 133.78, 135.33, 138.40, 158.46 ppm; HRMS (EI) calcd for $C_{23}H_{24}O$ $[M]^+$: 316.1827, found 316.1826.

2.3.2.1.5.*2-[2-(4-Methoxynaphthyl)vinyl]naphthalene (**2f**):* Yellow needle-like crystal, Mp=167–168ºC. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=4.04 (3H, s, -OMe), 6.88 (1H, d, *J*=8.5Hz), 7.20 (1H, s), 7.25 (1H, s),7.43-7.48 (2H, m), 7.53 (1H, dt, *J*=8.0, 1.0 Hz), 7.58 (1H, dt, *J*=8.0, 1.5 Hz), 7.74 (1H, d, *J*=8.0Hz), 7.82-7.85 (2H, m), 7.88 (1H, d, *J*=16.0Hz), 7.94 (1H, d, *J*=16.0Hz), 8.22 (1H, d, *J*=8.5 Hz), 8.33 (1H, dd, *J*=8.5, 1.0 Hz) ppm;^{13}C NMR (125 MHz, $CDCl_3$): δ=55.83, 104.16, 122.75, 123.78, 123.93, 124.11, 125.46, 125.84, 126.01, 126.31, 126.56, 126.94, 127.76, 127.95, 128.21, 128.55, 130.10, 132.50, 133.17, 134.02, 135.68, 155.72 ppm; HRMS (EI) calcd for $C_{23}H_{18}O$ $[M]^+$: 310.1357, found 310.1363.

2.3.2.2. General Procedure for the Preparation of 2-Methoxybenzo[c]phenanthrene Derivatives (3a-f).

2a (2.60 g, 10 mmol) was dissolved in cyclohexane (1400 ml) and then iodine (2.80 g,11 mmol) and propylene oxide (5ml) were added. The reaction mixture was irradiated by *hv* for approximately8 h to produce **3a**. The mixture was then washed with10% sodium thiosulfate (50 ml)followed by an additional wash inbrine solution (10 ml).Next, the mixture was dried over anhydrous sodium sulfate. Eventually, the product was purified by flash column chromatography(*n*-hexane/ethyl acetate=10/1). The product was recrystallized from cyclohexane with a 53% yield andan Mp=65–68°C. But in the case of bromo substituted derivatives **3e** and **3g,** the non substituted benzo[c]phenanthrene **3a** and benzo[c]chrysene **3f** were subjected into bromination reaction with pyridinium tribromide in presence of $CHCl_3$. The resulted mixtures were gently stirred at room temperature about 24 hours. Later, the solutions were dried at reduce pressure and recrystalized in cyclohexane to obtain white needle like crystal of **3e** and **3g** with a good yields.

Table 2.4 Photocyclization reaction of (*E*)-Stilbene derivatives



2 **3**

Entry[a,b]	Substrate/R_1, R_2, R_3	Reaction Condition **2 : I_2**	Time/h	**3** (Yield%)[b]
1	**2a:** R_1, R_2, R_3 /H		8	**3a** (75)
2	**2b:** R_1/Me, R_2, R_3/H		7	**3b** (45)
3	**2c:** R_1/Et, R_2, R_3/H	1 **:** 1.2	7	**3c** (78)
4	**2d:** R_1/^{t}Bu, R_2, R_3/H		7	**3d** (72)
5	**2f:** R_1,R_2/Benzo, R_3/H		7	**3f** (68)

[a]All reactions were carried out under *hv* light (450 W high-pressure mercury lamp at 50Hz).
[b]For all reactions propylene oxide was used as HI scavenger (5-35ml).
[c]Isolated yield.

2.3.2.2.1. *2-Methoxybenzo[c]phenanthrene (**3a**):* White crystal, Mp=65–68ºC. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=4.02 (3H, s), 7.29 (1H, dd, *J*=8.5, 2.0 Hz), 7.61 (1H, t, *J*=7.5Hz), 7.67

(1H, t, t, *J*=7.5 Hz), 7.70 (1H, d, *J*=8.0 Hz), 7.81 (1H, d, *J*=8.5 Hz),7.83 (1H, d, t, *J*=8.5 Hz),7.88 (1H, d, *J*=8.5 Hz),7.93 (1H, d, *J*=8.5 Hz), 8.01 (1H, dd, *J*=7.5, 1.0 Hz), 8.60 (1H, d, *J*=2.5 Hz), 9.20 (1H, d, *J*=8.5 Hz) ppm; HRMS (EI) calcd for $C_{19}H_{14}O$ $[M]^+$: 258.1044, found 258.1042.

2.3.2.2.2. *2-Methoxy-3-methylbenzo[c]phenanthrene (**3b**):* Brown oily compound. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=2.81 (3H, s,-Me), 4.20 (3H, s,-OMe), 7.87-8.10 (6H, m), 8.26 (1H, d, *J*=8.5 Hz), 8.48 (1H, d, *J*=8.0 Hz), 8.82 (1H, s), 9.55 (1H, d, *J*=8.5 Hz) ppm; HRMS (EI) calcd for $C_{20}H_{16}O$ $[M]^+$: 272.1201, found 272.1198.

2.3.2.2.3. *2-Methoxy-3-ethylbenzo[c]phenanthrene (**3c**):* Brown oily compound.^{1}H NMR ($CDCl_3$, 500 MHz): δ=1.30 (3H, t, *J*=7.5 Hz), 2.78 (2H, q, *J*=7.5Hz), 3.99 (3H, s, -OMe), 7.15-7.88 (7H, m), 7.96 (1H, d, *J*=8.0 Hz), 8.49 (1H, s), 9.19 (1H, d, *J*=8.5 Hz) ppm; HRMS (EI) calcd for $C_{21}H_{18}O$ $[M]^+$: 286.1357, found 286.1354.

2.3.2.2.4. *2-Methoxy-3-tert-butylbenzo[c]phenanthrene (**3d**):* Brown oily compound. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=1.54 (9H, s, $(-CH_3)_3$), 4.07 (3H, s,-OMe), 7.59–7.70 (3H, m), 7.79–7.87 (4H, m), 8.01 (1H, dd, *J*=7.5, 1.5 Hz), 8.56 (1H, s), 9.24 (1H, d, *J*=8.5 Hz) ppm; HRMS (EI) calcd for $C_{23}H_{22}O$ $[M]^+$: 314.1670, found 314.1669.

2.3.2.2.5. *6-Bromo-2-methoxybenzo[c]phenanthrene (**3e**):* Pale brown crystal, Mp=125–127°C. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=4.00 (3H, s), 7.29 (1H, d, *J*=10.0 Hz), 7.62-7.68 (2H, m), 7.84 (1H, d, *J*=8.5 Hz), 7.96 (1H, d, *J*=9.0 Hz), 8.05 (1H, d, *J*=9.5 Hz), 8.16 (1H, s), 8.33 (1H, d, *J*=9.0 Hz), 8.49 (1H, s), 9.12 (1H, d, *J*=9.5 Hz) ppm;^{13}C NMR ($CDCl_3$, 125 MHz): δ=55.59, 109.45, 117.22, 118.83, 125.52, 126.40, 127.4, 28.29, 28.54, 128.55, 128.57, 129.03, 129.52, 130.02, 130.43, 130.82, 133.32, 158.36 ppm; HRMS (EI) calcd for $C_{19}H_{13}BrO$ $[M]^+$: 336.0149, found 336.0145.

2.3.2.2.6. *8-Methoxybenzo[c]chrysene (**3f**):* Pale brown plate-like crystal, Mp=126-129ºC. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=4.16 (3H, s, -OMe), 7.61 (1H, dt, *J*=8.5, 1.5 Hz), 7.67 (1H, dt, *J*=8.0, 1.5 Hz), 7.72 (1H, dt, *J*=8.0, 1.5 Hz), 7.76 (1H, dt, *J*=8.5, 1.5 Hz),7.84 (1H, d, *J*=8.5 Hz), 7.87 (1H, d, *J*=8.5 Hz), 8.00 (1H, d, *J*=8.5 Hz), 8.02 (1H, dd, *J*=9.0, 1.5 Hz), 8.40 (1H, s), 8.42 (1H, d, *J*=8.5 Hz), 8.71 (1H, d, *J*=8.5 Hz), 8.75 (1H, d, *J*=8.5 Hz), 9.16 (1H, d, *J*=8.5 Hz) ppm;^{13}C NMR (125 MHz, $CDCl_3$): 55.81, 103.51, 122.04, 122.59, 123.47, 124.90, 125.88, 125.95, 126.06, 126.59, 127.16, 127.48, 127.51, 127.59, 127.71, 128.91, 129.80,

130.78, 131.70, 131.73, 133.77, 153.93 ppm; HRMS (EI) calcd for $C_{23}H_{16}O$ $[M]^+$: 308.1201, found 308.1197.

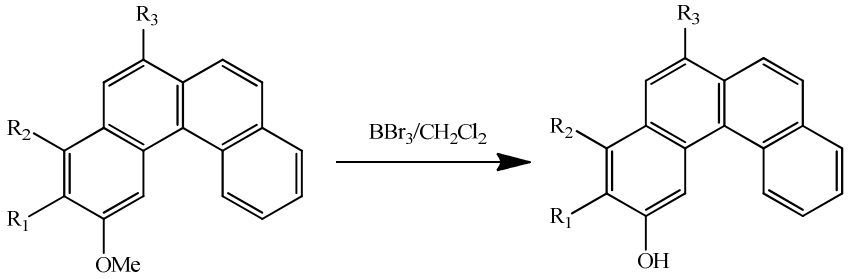
2.3.2.2.7. *14-Bromo-8-methoxybenzo[c]chrysene (**3g**):* Light yellow solid, Mp=149–152ºC. ^{1}H NMR ($CDCl_3$, 500 MHz): δ=4.14 (3H, s, -OCH_3), 7.65 (2H, m), 7.74 (1H, td, *J*=8.0, 1.0 Hz), 7.79 (1H, td, *J*=8.0, 1.0 Hz), 7.95 (1H, d, *J*=8.5 Hz), 8.03 (1H, dd, *J*=7.5, 1.0 Hz), 8.31 (1H, d, *J*=8.5 Hz), 8.33 (1H, s), 8.43 (1H, dd, *J*=8.0, 1.0 Hz) 8.69 (1H, d, *J*=8.5 Hz), 9.00 (1H, s), 9.12 (1H, d, *J*=8.5 Hz) ppm;^{13}C NMR ($CDCl_3$, 125 MHz): δ=55.83, 103.54, 119.69, 122.67, 123.33, 125.70, 126.03, 126.05, 126.14, 126.77, 127.08, 127.80, 128.12, 128.56, 128.81, 129.22, 129.38, 129.88, 130.30, 130.66, 133.65, 154.08 ppm; HRMS (EI) calcd for $C_{23}H_{15}BrO$ $[M]^+$: 386.0306, found 386.0302.

2.3.2.3. General Procedure for the Synthesis of 2-Hydroxybenzo[c]phenanthrene Derivatives (4a-g).

***Method A**:* **3a** (1.29 g, 5.0 mmol), NaH (0.96g, 25mmol), EtSH (1.85ml, 25mmol) and DMF (5ml) were charged in a round bottom flask and the reaction mixture was stirred at 100°C for 2 days. Next, the reaction mixture was neutralized with 4N HCl and extracted with toluene. The organic phases were dried over anhydrous sodium sulfate. Lastly, the product (**4a**) was purified by flash column chromatography (*n*-hexane/ethyl acetate=7/3). The product was then recrystallized utilizing cyclohexane with an 83% yield and an Mp=109-112°C.

Method B**:3b** (1.14 g, 4.2 mmol) and a 1 M boron tribromide/dichloromethane solution (4.5 ml, 4.5 mmol) were charged in a round bottom flask and stirred at room temperature for 20h. Next, water was added to the reaction mixture followed by extraction with chloroform (10 ml × 3). The organic phases were dried over anhydrous sodium sulfate and concentrated. Eventually, the crude product was purified by column chromatography (silica gel, developing solvent: chloroform) and the desired product **4b** was obtained as a red oil with an 89% yield.

Table 2.5 Demethylation reaction of 2-methoxy benzo[c]phenanthrene derivatives



3 **4**

Entry[a]	Substrate/R_1, R_2, R_3	Reaction Condition **3 :** BBr_3/CH_2Cl_2	Time/h	**4** (Yield%)[b]
1	**3a:** R_1, R_2, R_3 /H		24	**4a** (83)
2	**3b:** R_1/Me, R_2, R_3/H		20	**4b** (89)
3	**3c:** R_1/Et, R_2, R_2/H		20	**4c** (34)
4	**3d:** R_1/^{t}Bu, R_2, R_3/H	1 **:** 2	16	**4d** (89)
5	**3e:** R_1, R_2,/H, R_3/Br		24	**4e** (85)
6	**3f:** R_1,R_2/Benzo, R_3/H		16	**4f** (89)
7	**3g:** R_1,R_2/Benzo,R_3/Br		24	**4g** (85)

[a]All reactions were carried out at room temperature.
[b]Isolated yield.

2.3.2.3.1. *2-Hydroxybenzo[c]phenanthrene (**4a**):* White solid, Mp=119–121ºC; ^{1}H NMR ($CDCl_3$, 500 MHz): δ=5.11 (1H, s, -OH), 7.22 (1H, dd, *J*=9.0, 2.5 Hz), 7.59 (1H, t, *J*=7.5 Hz), 7.64 (1H, t, *J*=7.5 Hz), 7.868 (1H, d, *J*=8.5 Hz), 7.89 (1H, d, *J*=9.0 Hz), 7.94 (1H, d, *J*= 9.0 Hz), 8.01 (1H, d, *J*=8.0 Hz), 8.55 (1H, d, *J*=2.5 Hz), 9.12 (1H, d, *J*=8.5 Hz) ppm; ^{13}C NMR ($CDCl_3$, 125MHz): δ=111.85, 116.56, 124.90, 125.92, 126.35, 126.51, 127.18, 127.49, 128.80, 128.84, 128.847, 130.61, 130.74, 131.83, 131.92, 133.54, 154.39 ppm; HRMS (EI) calcd for $C_{18}H_{12}O$ $[M]^+$: 244.0888, found 244.0886.

2.3.2.3.2. *2-Hydroxy-3-methylbenzo[c]phenanthrene (**4b**):* Red oily compound, ^{1}H NMR ($CDCl_3$, 500 MHz): δ=2.45 (3H, s,-Me), 5.38 (1H, s,-OH), 7.18 (1H, s), 7.54 (1H, t, *J*=9.0 Hz), 7.61 (1H, d, *J*=8.5 Hz), 7.71 (1H, d, *J*=8.0 Hz), 7.72 (1H, t, *J*=9.0 Hz), 7.73 (1H, d, *J*=8.0 Hz), 7.79 (1H, d, *J*=8.0 Hz), 7.93 (1H, dd, *J*=8.0, 1.5 Hz), 8.46 (1H, s), 9.06 (1H, d, *J*=8.0 Hz) ppm;^{13}C NMR ($CDCl_3$, 125MHz): δ=16.39, 111.33, 124.81, 125.17, 125.33,

125.80, 126.20, 127.06, 127.29, 127.35, 127.43, 127.67, 128.83, 129.49, 130.56, 130.73, 131.25, 131.31, 153.49 ppm; HRMS (EI) calcd for $C_{19}H_{14}O$ $[M]^+$: 258.1044, found 258.1044.

2.3.2.3.3. *2-Hydroxy-3-ethylbenzo[c]phenanthrene (**4c**):* Red oily compound, ^{1}H NMR ($CDCl_3$, 500 MHz): δ=1.42 (3H, t, *J*=7.5 Hz), 2.90 (2H, q, *J*=7.5 Hz), 5.14 (1H, s, -OH), 7.59-7.69 (3H, m), 7.78–7.86 (5H, m), 8.49 (1H, s), 9.13 (1H, d, *J*=8.5Hz) ppm;^{13}C NMR ($CDCl_3$, 125MHz): δ=14.09, 23.45, 111.53, 124.77, 125.46, 125.79, 126.19, 127.24, 127.29, 127.34, 127.44, 127.76, 128.82, 128.83, 129.17, 130.18, 130.73, 131.28, 131.32, 153.12ppm; HRMS (EI) calcd for $C_{20}H_{16}O$ $[M]^+$: 272.1201, found 272.1202.

2.3.2.3.4. *2-Hydroxy-3-(tert-butyl)benzo[c]phenanthrene (**4d**):* Red oily compound, ^{1}H NMR ($CDCl_3$, 500 MHz): δ=1.57 (9H, s, $[-CH_3]_3$), 5.34 (1H, s,-OH), 7.58 (1H, t, *J*=7.5 Hz), 7.61 (1H, dt, *J*=8.5, 1.5 Hz), 7.67 (1H, d, *J*=8.5 Hz), 7.78 (1H, d, *J*=8.5 Hz), 7.82 (1H, d, *J*=8.5 Hz), 7.85 (1H, d, *J*=7.5 Hz), 7.87 (1H, s), 8.00 (1H,dd, *J*=8.0, 1.0 Hz), 8.40 (1H, s), 9.13 (1H, d, *J*=8.0 Hz) ppm;^{13}C NMR ($CDCl_3$, 125 MHz): δ=29.92, 35.12, 112.89, 124.65, 125.75, 125.83, 126.14, 127.17, 127.33, 127.34, 127.35, 127.70, 128.87, 128.90, 130.05, 130.73, 131.45, 133.51, 137.47, 153.98 ppm; HRMS (EI) calcd for $C_{22}H_{20}O$ $[M]^+$: 300.1514, found 300.1513.

2.3.2.3.5. *6-Bromo-2-hydroxybenzo[c]phenanthrene (**4e**):* White solid, Mp=182–185ºC, ^{1}H NMR ($CDCl_3$, 500 MHz): δ= 5.11 (1H, s), 7.23–7.22 (1H, dd, *J*=8.5 Hz), 7.69–7.62(2H, m), 7.83 (1H, d, *J*=10.0 Hz), 7.97 (1H, d, *J*=5.0 Hz), 8.02–8.05 (1H, m), 8.16 (1H, s), 8.33 (1H, d, *J*=9.0 Hz), 8.46 (1H, d, *J*=2.0 Hz), 9.07 (1H, d, *J*=8.5 Hz) ppm; ^{13}C NMR ($CDCl_3$, 125MHz): δ=112.26, 117.34, 119.16, 125.70, 126.66, 126.68, 127.70, 128.46, 128.66, 128.72, 128.83, 129.71, 129.81, 130.19, 130.70, 131.18, 133.50, 154.53 ppm; HRMS (EI) calcd for $C_{18}H_{11}BrO$ $[M]^+$: 321.9993, found 321.9998.

2.3.2.3.6. *8-Hydroxybenzo[c]chrysene (**4f**):* Light brown needle-like crystal, Mp=174–175ºC;^{1}H NMR ($CDCl_3$, 500 MHz): δ=5.53 (1H, s, -OH), 7.60 (1H, dt, *J*=8.0, 1.5 Hz), 7.62 (1H, dt, *J*=8.0,1.5 Hz), 7.71 (1H, dt, *J*=7.5, 1.0 Hz), 7.75 (1H, dt, *J*=8.0, 1.5 Hz), 7.83 (1H, d, *J*=8.5 Hz), 7.86 (1H, d, *J*=9.0 Hz), 7.89 (1H, d, *J*=8.5 Hz), 8.00 (1H, dd, *J*=7.5, 1.0 Hz), 8.01 (1H, dd, *J*=8.5, 1.0 Hz), 8.39 (1H, s), 8.73 (1H, d, *J*=8.5 Hz), 8.80 (1H, d, *J*=8.5 Hz), 9.06 (1H, d, *J*=8.5 Hz) ppm;^{13}C NMR ($CDCl_3$, 125 MHz): δ=107.53, 122.07, 122.31, 123.67, 124.74, 124.98, 126.03, 126.09, 126.23, 126.61, 126.99, 127.08, 127.57, 127.70, 127.95,

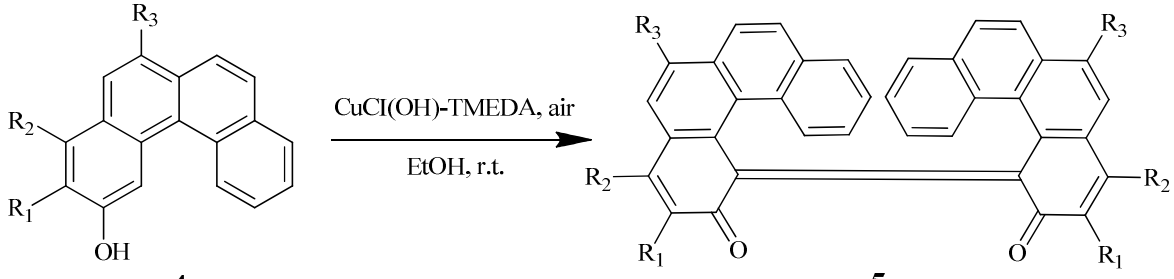
128.82, 129.61, 130.66, 131.70, 132.02, 133.70, 150.03 ppm; HRMS (EI) calcd for $C_{22}H_{14}O$ $[M]^+$: 294.1044, found 294.1043.

2.3.2.3.7. *14-Bromo-8-hydroxybenzo[c]chrysene(**4g**):* White solid, Mp=210–214ºC;^{1}H NMR ($CDCl_3$, 500 MHz): δ=5.69 (1H, s, -OH), 7.68 (2H, m), 7.74 (1H, td, *J*=8.0, 1.0 Hz), 7.79 (1H, td, *J*=8.0, 1.0 Hz), 7.96 (1H, d, *J*=8.5 Hz), 8.04 (1H, dd, *J*=7.5, 1.0 Hz), 8.31 (1H, d, *J*=8.5 Hz), 8.33 (1H, s), 8.39 (1H, dd, *J*=8.0, 1.0 Hz) 8.73 (1H, d, *J*=8.5 Hz), 9.03 (1H, d, *J*=8.5 Hz) ppm; ^{13}C NMR ($CDCl_3$, 125 MHz): δ=107.52, 119.76, 122.43, 123.54, 124.98, 125.66, 126.08, 126.32, 126.50, 126.79, 127.12, 127.91, 128.38, 128.67, 128.74, 129.05, 129.87, 130.19, 130.99, 131.95, 133.59, 150.32 ppm; HRMS (EI) calcd for $C_{22}H_{13}BrO$ $[M]^+$: 372.0149, found 372.0145.

2.3.2.4. General Procedure for the Preparation of Quinone Derivatives (5a-g).

4a (0.244 g, 1.0 mmol) and CuCl(OH)–TMEDA (0.0232g, 0.10 mmol) were mixed in a reaction vessel with ethanol and gently stirred at room temperature for 24 h under aerobic conditions. The product **5a** was then separated by filtration and washed with ethanol with a 90% yield and an Mp=228-230°C. For **5f** and **5g**, oxidative coupling reactions produced keto products. The keto products were then refluxed in toluene for 1-4 h to obtain quinone derivatives.

Table 2.6 Oxidative coupling reactions of 2-hydroxybenzo[c]phenanthrene derivatives



4 **5**

Entry[a]	Substrate/R_1, R_2, R_3	ReactionCondition **4 :** CuCl(OH)TMEDA	Time/h	**5** (Yield%)[b]
1	**4a:** R_1, R_2, R_3 /H		24	**5a** (90)

2	**4b:** R_1/Me, R_2, R_3/H		16	**5b** (39)
3	**4c:** R_1/Et, R_2, R_2/H		16	**5c** (48)
4	**4d:** R_1/^{t}Bu, R_2, R_3/H	1 : 0.1	16	**5d** (25)
5	**4e:** R_1, R_2,/H, R_3/Br		24	**5e** (98)
6	**4f:** R_1,R_2/Benzo, R_3/H		21	**5f** (69)
7	**4g:** R_1,R_2/Benzo,R_3/Br		24	**5g** (65)

[a]All reactions were carried out at room temperature in ethanol.
[b]Isolated yield.

2.3.2.4.1. *1,1'-Bibenzo[c]phenanthrylidene-2,2'-dione (**5a**):* Red crystal, Mp=228–230°C;IR(ATR): 303, 1685, 838cm^{-1};^{1}H NMR ($CDCl_3$, 500MHz): δ=6.43 (1H, d, *J*=9.5 Hz), 6.59 (1H, d, *J*=8.0 Hz), 6.85 (1H, d, *J*=8.0Hz), 6.92 (1H, d, *J*=8.5 Hz), 7.07 (1H, d, *J*=8.0 Hz), 7.19 (1H, d, *J*=9.0 Hz), 7.34-7.40 (2H, m), 7.47 (1H, d, *J*=8.0 Hz), 8.73 (1H, d, *J*=7.5 Hz) ppm; ^{13}C NMR ($CDCl_3$, 125MHz): δ=125.37, 125.86, 126.16, 126.46, 126.64, 127.00, 127.39, 127.41, 127.89, 129.28, 130.01, 131.40, 132.02, 133.08, 133.59, 144.54, 144.68, 197.48 ppm; HRMS (EI) calcd for $C_{36}H_{20}O_2$ $[M]^+$: 484.1463, found 484.1458.

2.3.2.4.2. *3,3'-Dimethyl-1,1'-bi[benzo[c]phenanthrenylidene]-2,2'-dione (**5b**):* Red crystal, Mp=165–168°C, IR (ATR): 3007, 2918, 1670cm^{-1};^{1}H NMR ($CDCl_3$, 500 MHz): δ=2.23 (6H, s, -Me), 6.52 (2H, d, *J*=8.0 Hz), 6.80 (2H, d, *J*=8.0 Hz), 6.85 (2H, s), 6.87 (2H, d, *J*=9.0 Hz), 7.14 (2H, d, *J*=8.5 Hz), 7.31 (2H, dt, *J*=7.5, 1.5 Hz), 7.35 (2H, dt, *J*=7.5, 1.5 Hz), 7.44 (2H, d, *J*=8.0 Hz), 8.69 (2H, d, *J*=8.0 Hz):^{13}C NMR ($CDCl_3$, 125 MHz): δ=15.24, 125.38, 125.77, 125.87, 126.33, 126.83, 126.91, 127.23, 128.16, 129.15, 129.71, 130.76, 132.19, 132.52, 133.47, 135.34, 140.36, 145.07, 199.37 ppm; HRMS (EI) calcd for $C_{38}H_{24}O_2$ $[M]^+$: 512.1776, found 512.1772.

2.3.2.4.3. *3,3'-Diethyl-1,1'-bi[benzo[c]phenanthrenylidene]-2,2'-dione (**5c**):* Red crystal, Mp=258–262ºC, IR (ATR): 2960, 1680, 836, 746cm^{-1};^{1}H NMR ($CDCl_3$, 500 MHz): δ=1.41 (6H, t, *J*=7.5 Hz), 2.54 (2H, q, *J*=7.5 Hz), 2.77 (2H, q, *J*=8.0 Hz), 6.53 (2H, d, *J*=8.0 Hz), 6.77 (2H, s), 6.80 (2H, d, *J*=8.5 Hz), 6.88 (2H, d, *J*= 8.5 Hz), 7.15 (2H, d, *J*=8.5 Hz), 7.31 (2H, dt, *J*=8.0, 1.5 Hz), 7.37 (2H, d, *J*=7.0 Hz), 7.45 (2H, d, *J*=7.5 Hz), 8.71 (2H, d, *J*=8.5 Hz) ppm; ^{13}C NMR ($CDCl_3$, 125 MHz): δ=13.52, 22.31, 125.51, 125.73, 125.79, 126.25, 126.69, 126.77, 127.20, 128.68, 129.04, 130.48, 130.77, 131.66, 132.50, 133.84, 138.48,

141.25,141.29, 192.40 ppm; HRMS (EI) calcd for $C_{40}H_{28}O_2$ $[M]^+$: 540.2089, found 540.2082.

2.3.2.4.4. *3,3'-Di-tert-butyl-1,1'-bi[benzo[c]phenanthrenylidene]-2,2'-dione (**5d**):* Red crystal, Mp=198–203ºC, IR (ATR): 3047, 2951, 2869, 1680, 1364 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz): δ=1.53 (18H, s,), 6.53 (2H, d, *J*=8.0 Hz), 6.79 (2H, d, *J*=7.5 Hz), 6.81 (2H, s), 6.87 (2H, d, *J*=8.5 Hz), 7.13 (2H, d, *J*=8.5 Hz), 7.28 (2H, dt, *J*=8.5, 1.0 Hz), 7.36 (2H, dt, *J*=8.0, 1.0 Hz), 7.44 (2H, d, *J*=7.5 Hz), 8.74 (2H, d, *J*=8.0 Hz) ppm;^{13}C NMR ($CDCl_3$, 125 MHz): δ=30.13, 35.38, 125.41, 125.53, 125.70, 125.92, 126.40, 126.48, 126.95, 128.00, 128.67, 129.26, 130.50, 131.84, 131.91, 133.19, 137.26, 144.82, 146.95, 199.59 ppm; HRMS (EI) calcd for $C_{44}H_{36}O_2$ $[M]^+$: 596.2715, found 596.2711.

2.3.2.4.5. *6,6'-Dibromo-1,1'-bi[benzo[c]phenanthrenylidene]-2,2'-dione (**5e**):* Red crystal, Mp=268–272ºC, IR (ATR): 3063, 1688, 811, 751cm^{-1};^1H NMR ($CDCl_3$, 500 MHz): δ=6.42 (1H, d, *J*=9.5 Hz), 6.81 (1H, s), 6.92 (1H, d, *J*=10.5 Hz), 9.05 (1H, s), 7.37–7.42 (2H, m), 7.45 (1H, t, *J*=7.0 Hz), 7.66 (1H, d, *J*=8.0 Hz), 8.59 (1H, d, *J*=8.0 Hz) ppm; HRMS (EI) calcd for $C_{36}H_{18}Br_2O_2$ $[M]^+$: 639.9673, found 639.9661.

2.3.2.4.6. *8H,8'H-[7,7'-Bibenzo[c]chrysenylidene]-8,8'-dione (**5f**):* Orange crystal, Mp=285-287ºC, IR (ATR): 3039, 3027, 1667, 1277cm^{-1};^1H NMR ($CDCl_3$, 500 MHz): δ=6.85 (1H, dt, *J*=7.5, 1.5 Hz), 6.95 (1H, d, *J*=8.0 Hz), 6.96 (1H, d, *J*=8.5 Hz), 7.19 (1H, d, *J*=8.5 Hz), 7.22 (1H, d, *J*=8.5 Hz), 7.33 (1H, dt, *J*=7.5, 1.0 Hz), 7.51 (2H, dt, *J*=7.5, 1.0 Hz), 7.61 (1H, d, *J*=8.0 Hz), 7.69 (1H, td, *J*=7.5, 1.0 Hz), 8.14 (1H, dd, *J*=8.0, 1.0 Hz), 8.45 (1H, d, *J*=8.5 Hz) ppm; ^{13}C NMR ($CDCl_3$, 125 MHz): δ=121.26, 122.24, 123.75, 125.11, 125.63, 126.40, 127.01, 127.02, 127.63, 128.36, 128.93, 129.23, 129.29, 129.34, 131.60, 132.48, 132.67, 133.29, 134.33, 138.24, 142.43, 195.27 ppm; HRMS (EI) calcd for $C_{44}H_{24}O_2$ $[M]^+$: 584.1776, found 584.1783.

2.3.2.4.7. *14,14'-Dibromo-8H,8'H-[7,7'-bibenzo[c]chrysenylidene]-8,8'-dione (**5g**):* Red crystal, Mp>300ºC, IR (ATR): 3045, 1669, 1237cm^{-1};^1H NMR ($CDCl_3$, 500 MHz): δ=6.85 (1H, dt, *J*=7.5, 1.5 Hz), 7.15 (1H, d, *J*=8.0 Hz), 7.44 (3H, m), 7.53 (2H, dt, *J*=7.5, 1.0 Hz), 7.69 (2H, td, *J*=7.5, 1.0 Hz), 8.15 (1H, dd, *J*=8.0, 1.0 Hz), 8.33 (1H, d, *J*=8.5 Hz) ppm; ^{13}C NMR ($CDCl_3$, 125 MHz): δ=123.57, 124.37, 125.28, 125.89, 126.94, 127.02, 127.33, 127.61, 127.68, 128.24, 128.45, 128.66, 129.26, 129.50, 129.93, 130.68, 132.34, 132.61, 132.52,

134.52, 136.79, 193.96 ppm; HRMS (EI) calcd for $C_{44}H_{22}Br_2O_2$ $[M]^+$: 739.9986, found 739.9974.

2.4 CONCLUSION

In this chapter, we have successfully synthesized and characterized a new class of functional helical quinone derivatives **5a-g** in racemic form (*P/M*). Helical compounds are valuable for several applications. Therefore, our strategy offers a feasible methodology for the construction of novel helical quinone molecules, which are the sole compounds for the synthesis of many oxa[9]helicenes and its derivatives. Many of the oxa[9]helicene derivatives show photoelectric activity in thin film,[21,22] and we are currently investigating this application in collaboration with another research group. Furthermore, the optical resolution and diastereomeric separation of quinone derivatives is investigated in another chapter.

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CHAPTER 3

Synthesis of novel BIPOL ([1,1'-bibenzo[c] phenanthrene]-2,2'-diol) type compounds using 5%Pd-C catalyst with excellent yield from quinone derivatives

Synopsis

A new class of BIPOL ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) type derivatives **2a-g** were synthesized using the conventional 5%Pd-C catalytic reduction process from quinone derivatives in excellent yields. The BIPOLs are characterized by different spectroscopic techniques (e.g. FTIR, ^{1}H NMR, ^{13}C NMR, MS, X-ray crystallography) and proposed the reaction mechanism as well.

CHAPTER 3

3.1 INTRODUCTION

BINOLs and BINOL type derivatives are the best-known representative of axially chiral molecules and was first prepared as a racemate in 1873 by von Richter. Since that date, the preparation of racemic BINOL has been widely studied.[1] Even though, syntheses of some optically pure BINOL derivatives by asymmetric oxidative coupling of naphthol derivatives have been successfully developed[2] but, this research field has still more to unveil. The true widespread use of catalytic hydrogenation reaction did not start until 1897 when Sabatier and his coworkers developed the reaction between hydrogen and organic compounds to a universal reduction method (Noble prize 1912). It is estimated that about one fourth of all reduction in organic chemistry has done by the following methods.

Many catalysts, certainly those most widely used such as platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), nickel (Ni), Raney nickel (Ni/Al alloy) are now commercially available. In our case, we used 5% Pd-C. The advantage of using heterogeneous catalyst (5%Pd-C) is that, it can be removed by filtration at the end of the reaction and the product is uncontaminated as well. Compare to other homogeneous and heterogeneous reagents with 5%Pd-C for reduction of quinone derivatives **1a-g,** it has been found to act as an efficient and inexpensive one. Although, Pd-C has successfully utilized in reduction process for a long time but recently a great achievement was done by Buchecker and coworkers when they first fortunately used Pd-C as a heterogeneous catalyst to conduct most famous Suzuki-Miyaura coupling reaction.[3] Till then a lot of research work have been done on Suzuki-Miyaura coupling reaction where Pd-C used as heterogeneous catalyst.[4] In 2002, Köhler and co-workers auspiciously applied Pd-C catalyst in Heck reaction.[5]

Most recently, we have reported the asymmetric synthesis of helical quinone derivatives by using chiral diamine-copper complexes.[6] The novel synthesis of oxa [9] helicenes by the reaction of helical quinines with Lawesson's reagent and phosphorus pentasulfide.[7] We have also shown the simplest way to synthesis of oxa [9] helicenes derivatives by using a large number alcohols[8] and thiols[9] as well.

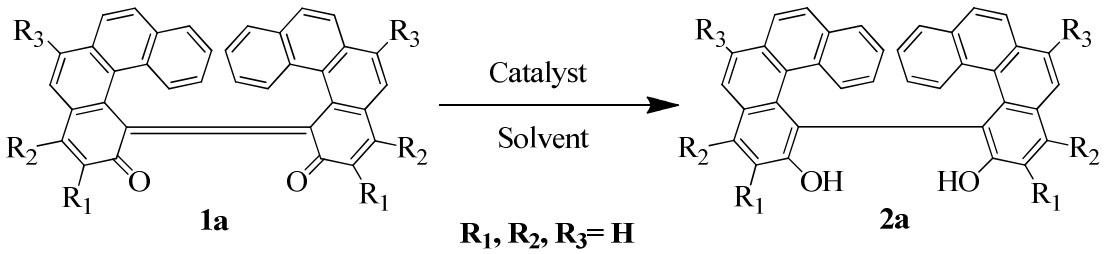
This chapter is the continuation of the previous chapter. Here I tried to show the best synthetic way of novel BIPOL ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) derivatives **2a-g** from quinone derivatives **1a-g** using the conventional catalytic reduction process. According

to the literature survey, reduction of benzo fused helical quinone derivatives **1a-g** using 5% Pd-C catalyst in H_2 atmosphere has not been done yet.

3.2 RESULTS AND DISCUSSIONS

At the beginning of the synthesis of BIPOL ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) derivatives **2a-g,** we investigated different reducing agents and catalyst (Table 3.1) on non substituted quinone **1a** to probe the influence of reductants on the chemical yields and selected the best reductant for our next substituted quinone derivatives **1b-g.** 1,1'-bisbenzo [c] phenanthrenylidene-2,2'-dione **1a** was subjected with various primary thiol in the presence of acid catalyst as a nucleophilic reagent. Among them 2-aminoethanethio reagent reduce quinone to [1,1'-bibenzo[c]phenanthrene]-2,2'-diol **2a** rather than neucleophilic addition reaction and the product yield was reasonable good (58% yield). When the same reagent (2-aminoethanethio) without acid catalyst was used and the result is quite better than the previous one (86% yield). After analyzing ^{1}H NMR spectra of acid catalyzed and non-acid catalyzed product **2a**, it was clear that there is no symmetrical change happened of the reduced form.

Table 3.1 Different reagents applied on non-substituted quinone (**1a**) reduction



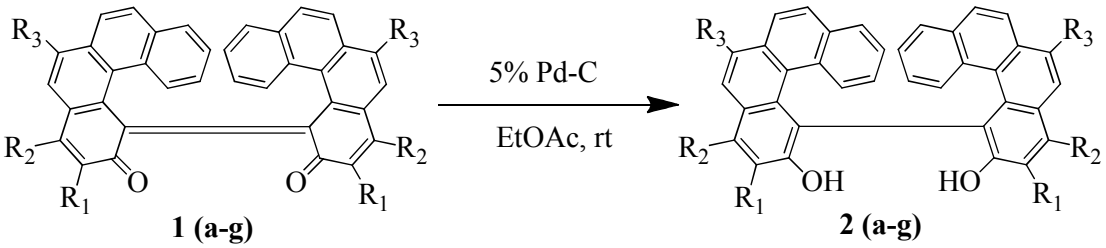
Entry [a]	Reagents / (equiv.)	Solvent	Catalyst / (equiv.)	Time / h	**2a** (% yield) [b]
1	**-**	**EtOAc**	**5%Pd-C (10 mg)**	**48**	**99**
2	$HS(CH_2)_2NH_2$	$CHCl_3$	HCl	24	58

	(1.1)		(3.0)		
3	**$HS(CH_2)_2NH_2$ (1.1)**	**$CHCl_3$**	**-**	**24**	**86**
4	$HS(CH_2)_2HS$ (1.0)	$CHCl_3$	-	24	-
5	Cysteine (1.0)	$CHCl_3$	-	24	-
6	$NH_2(CH_2)_2NH_2$ (1.0)	$CHCl_3$	-	24	-
7	**NH_2NH_2 (1.0)**	**$CHCl_3$**	**-**	**24**	**81**
8	$CH_3(CH_2)_3SH$ (1.1)	$CHCl_3$	HCl (1.5)	20	-
9	$PhCH_2SH$ (1.1)	$CHCl_3$	HCl (3.0)	24	-
10	^{t}BuSH (1.1)	$CHCl_3$	*p*TSA (3.0)	18	-
11	*ortho*-Aminophenol (2.0)	$CHCl_3$	-	24	75
12	$C_6H_5NHNH_2$ (3.0)	$CHCl_3$	-	24	65

[a]All reaction were carried out at room temperature.
[b]Isolated yield.

We have also used different primary amine, azide type reagents without acid catalyst. The azide showed some promising results as well (Table 3.1). Beside of all the reagents throughout our investigation 5% Pd-C catalyst in presence of H_2 atmosphere shows the best result. Although couples of reagents reduce the non-substituted quinoen **1a** quite well manner but in case of substituted quinones **1b-g** these reagents are not quite satisfactory at all. Finally, we selected 5% Pd-C catalyst for the reduction of our substituted quinone derivatives **1b-g** and the results are outstanding as well. In all instance, the products yields are excellent (Table 3.2).

Table 3.2 Reduction of quinone derivatives **1a-g**



Entry[a]	Substrate/R_1, R_2, R_3	EtOAc / ml	5%Pd-C / mg	%yield, **2(a-g)**[b]
1	**1a:** R_1, R_2, R_3 /H	15.0	10.0	100
2	**1b:** R_1/Me, R_2, R_3/H	20.0	10.0	96
3	**1c:** R_1/Et, R_2, R_2/H	15.0	10.0	95
4	**1d:** R_1/^{t}Bu, R_2, R_3/H	35.0	10.0	99
5	**1e:** R_1, R_2,/H, R_3/Br	25.0	10.0	90
6	**1f:** R_1,R_2/Benzo, R_3/H	30.0	10.0	**1f+2f**
7	**1g:** R_1,R_2/Benzo,R_3/Br	25.0	10.0	**1g+2g**

[a]All reaction were carried out at room temperature.
[b]Isolated yield.

However, in the case of **1f** and **1g** the reduced products are not stable at all. Because, when we try to recrystalized **2f** and **2g** in ethyl acetate solvent the resulting crystal was the starting quinone derivatives **1f** and **1g** which was confirmed by the ^{1}H NMR spectra data analysis. The reason might be, in presence of atmospheric oxygen **2f, 2g** oxidized quite easily to their quinone form **1f,** and **1g**. Nevertheless, why the reduce form of **1f, 1g** are unstable is still not clear to us.

Comparative ^{1}H NMR spectra of **1a** and **2a** shows that, the peak position of 10, 11, 12th proton of **2a** are shifted to the upfield position (Figure 3.1).

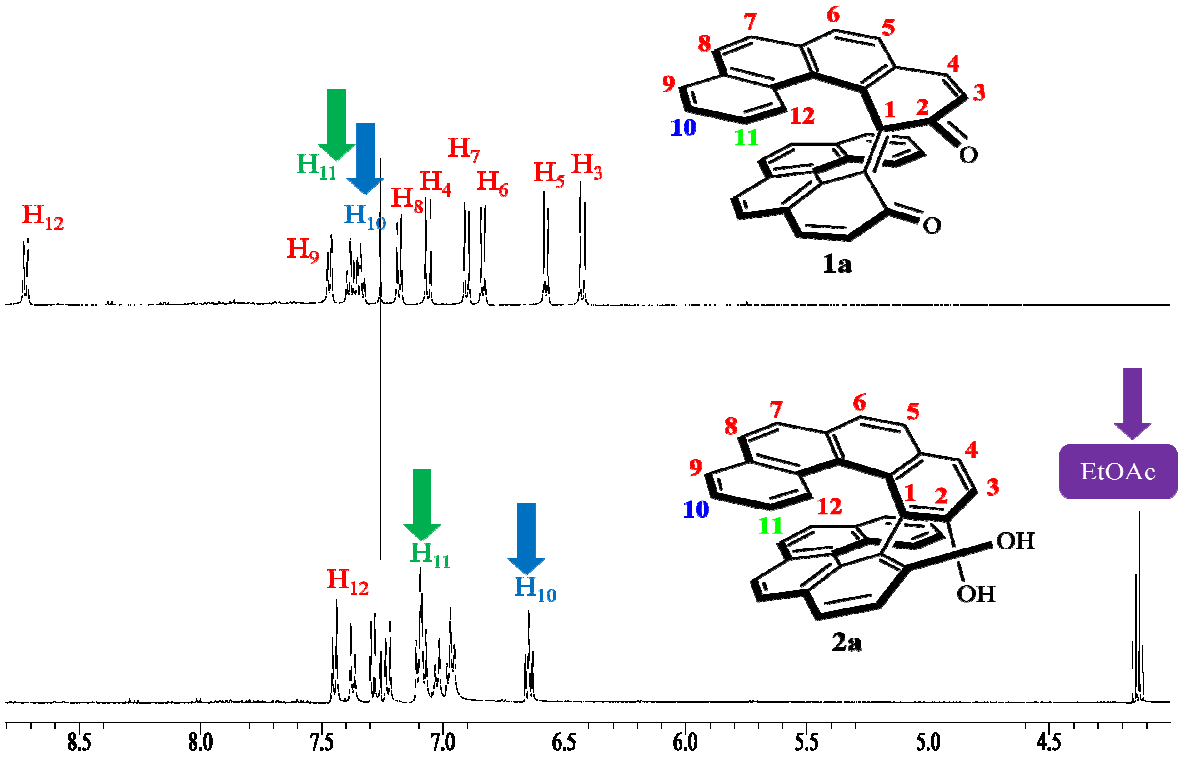


Figure 3.1 Comparative 1H NMR spectra of **1a** and **2a**

The reason behind the phenomenon might be, the 2-hydroxy benzo[c]phenanthrene moieties of the BIPOL ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) **2a** compound are more horizontal shape rather than vertical one. For that reason, the protons of 10, 11, 12th position of **2a** are more shielded than **1a**. Further, our assumption was supported by the X-ray crystallographic structure of **2a** (Figure 3.2).

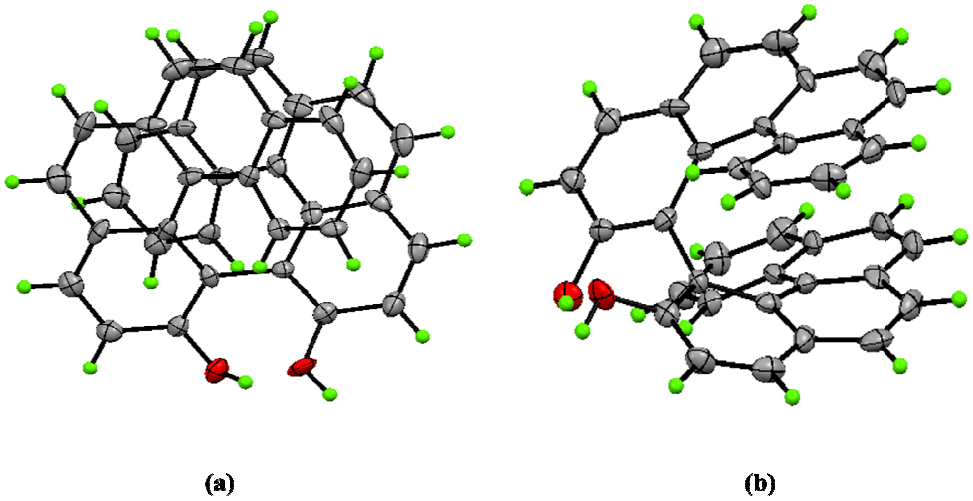


Figure 3.2 ORTEP drawing of **2a** (a) Top view and (b) Side view at 35% probability

Single-crystal X-ray analysis of **2a** established that, the compound was crystallized in the monoclinic $P2_1/c$ space group; their unit cell consists of two molecules one is "*S*" conformation and the other in "*R*" conformation.

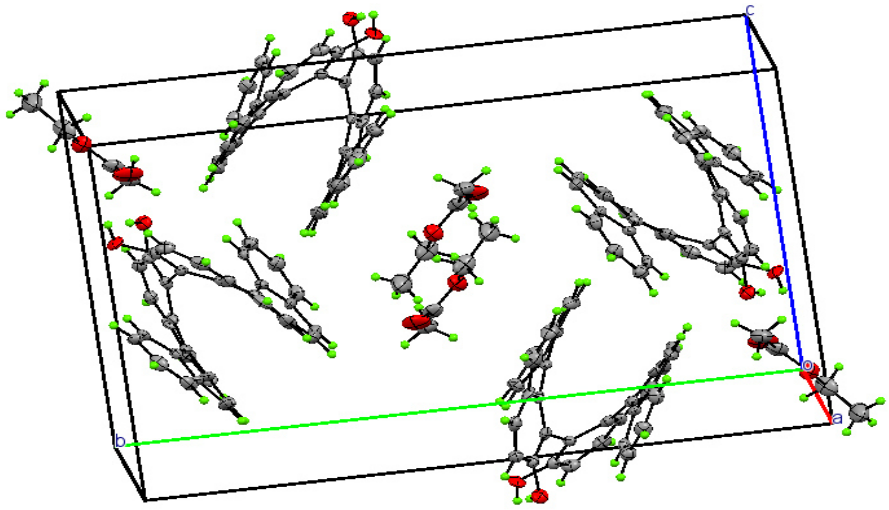
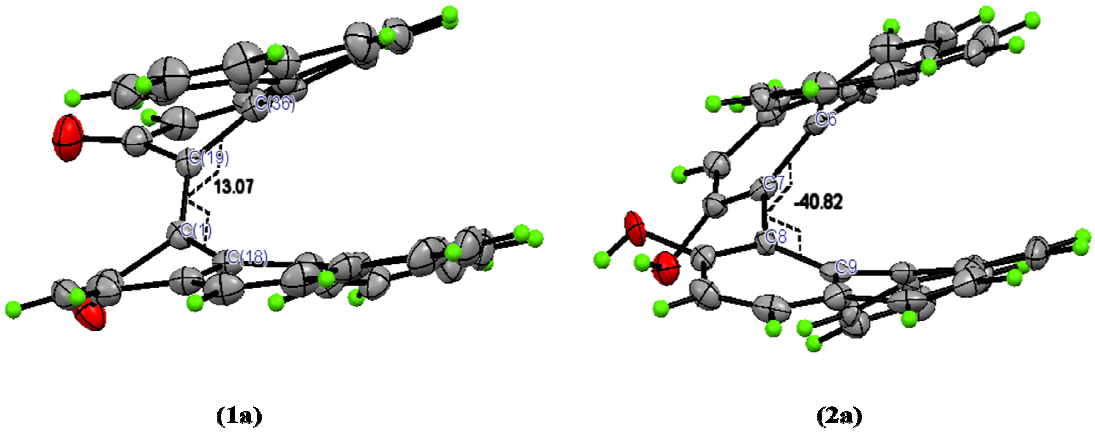


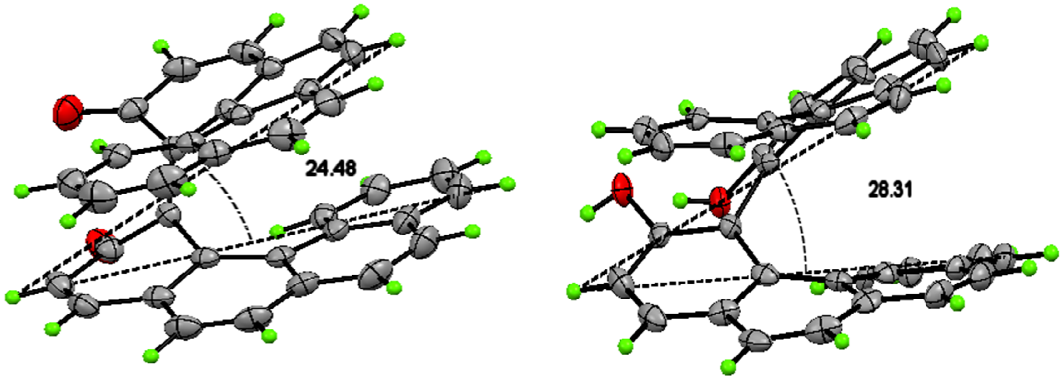
Figure 3.3 Unit cell structure of **2a** (Monoclinic $P2_1/c$ space group)

The dihedral angle of **2a** between two benzo[c]phenanathrene moieties is quite large value (40.82º) compare to quinone **1a** value (13.07º) and the angle between the two planes of **2a** reasonable large (28.3º) compared to its quinone **1a** (24.4º) precursor (Figure 3.3 and 3.4).



(1a) **(2a)**

Figure 3.4 Comparative torsional angles of **1a** and **2a**



(1a) **(2a)**

Figure 3.5 Comparative interplanner angles of **1a** and **2a**

The summation of inner torsional angles of **2a** was obtained 171.8º ; which is significantly much larger than those of literature values (e.g. for carbonyl linked 1,1'-bitriphenylene is 90.7 º and for 3,3-biphenanthrene based sila[7]helicene is 99.5º).[10] The large torsional angle value suggesting different degrees of distortion in the aromatic rings (Table 3.3).

Table 3.3 Selective dihedral angles (º) of **2a**

C-C bonds	Dihedral angle (º)
C24–C4–C5–C6	-19.0
C4–C5–C6–C7	-30.0

C5–C6–C7–C8	-15.0
C6–C7–C8–C9	**-40.8**
C7–C8–C9–C10	-18.0
C8–C9–C10–C11	-31.0
C9–C10–C11–C33	-18.0

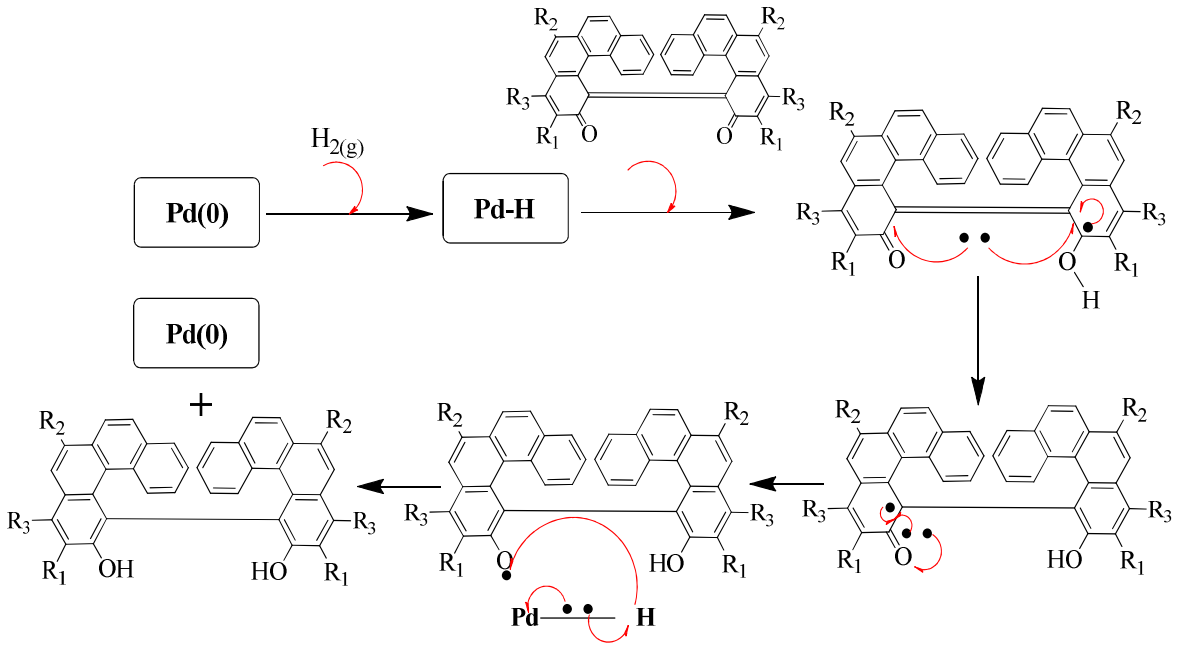
The bond length in the skeleton is also different. In comparison of the standard bond length of benzene (1.39 Å),[11] the range of C-C bond lengths of the inner helix was observed 1.399-1.466 Å, while the same on the outer periphery was shorter, as seen in the range of 1.336-1.365 Å (Table 3.4) clearly due to the much greater strain exerted in the inner carbon bonds.

Table 3.4 Selective inner and outer C-C bond length (Å) of **2a**

Entry	Inner Carbon	Bond length / Å	Outer Carbon	Bond length / Å
1	C24-C4	1.399	C1-C2	1.357
2	C4-C5	1.440	C21-C22	1.337
3	C5-C6	1.466	C18-C19	1.336
4	C6-C7	1.441	C15-C16	1.351
5	C8-C9	1.448	C34-C35	1.351
6	C9-C10	1.440	C27-C28	1.357
7	C10-C11	1.449	C30-C31	1.341
8	C11-C33	1.410	C13-C14	1.365

One of the possible catalytic reduction reaction mechanism was shown in Scheme 3.1. We know atomic hydrogen is a powerful reducing agent, but readily dimerizes to inactive molecular hydrogen. With rare exception normally H_2 does not take part any type of reaction with organic compounds below 480°C in the absence of metal catalyst.

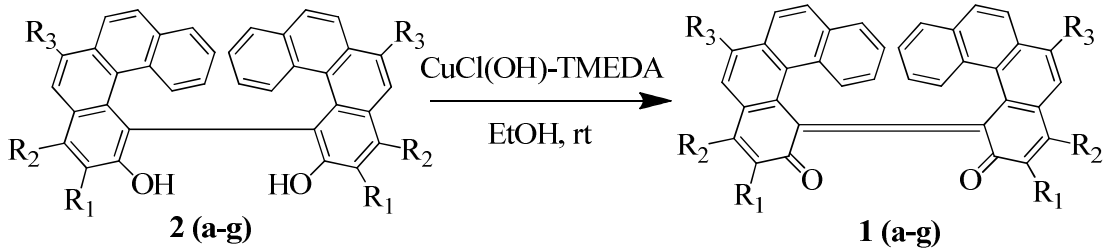
The 5%Pd-C catalyst facilitate the reduction process in presence of H_2 at room temperature (25°C) quite smoothly. The reason behind the reduction process is molecular hydrogen form metal surface hydride (Pd-H) and the hydrogen can be easily transferred to the chemisorbed quinone derivatives **1a-g** according to the manner shown in Scheme 3.1.



Scheme 3.1 Plausible reaction mechanism of quinone reduction

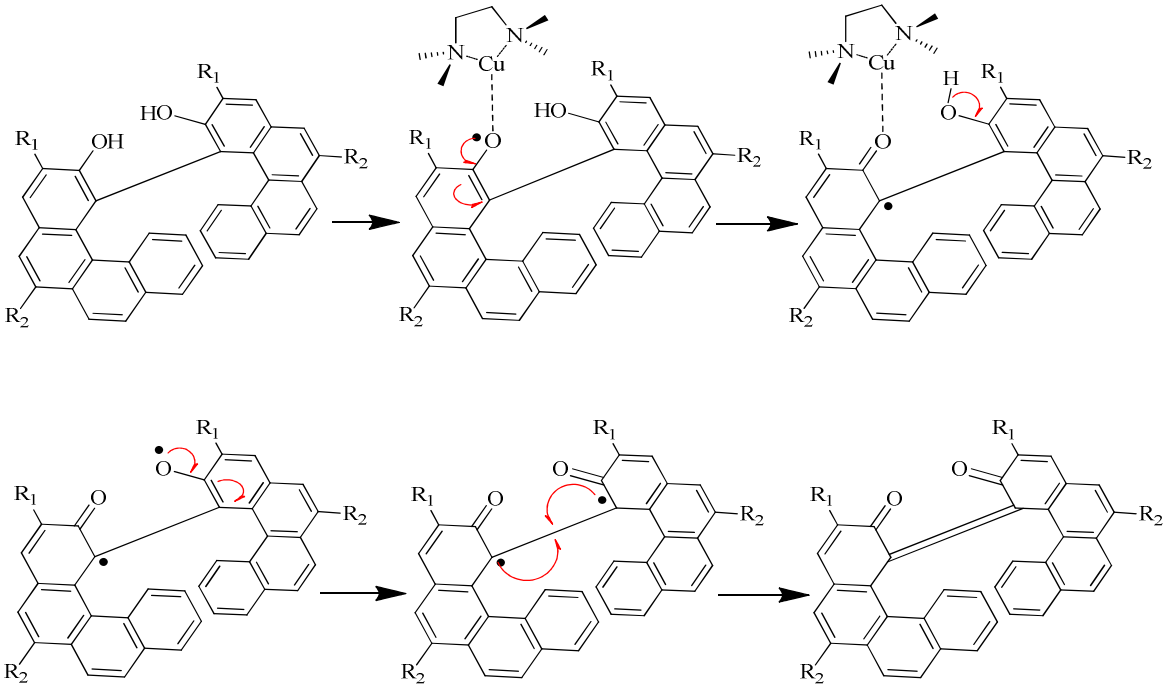
Our reduced products **2a-e** then subjected to the oxidation process in presence of CuCl(OH)-TMEDA catalyst with EtOH and the products yields were good (Table 3.5).

Table 3.5 Synthesis of quinone derivatives **1a-e** from **2a-e**



Entry[a]	Substrate/R_1, R_2, R_3	CuCl(OH)-TMEDA / mg	Time / h	%yield, **1(a-g)**
1	**2a:** R_1, R_2, R_3 /H	2.0	1	80
2	**2b:** R_1/Me, R_2, R_3/H	2.0	5	57
3	**2c:** R_1/Et, R_2, R_2/H	1.0	4	45

4	**2d:** R_1/^{t}Bu, R_2, R_3/H	4.0	3	52
5	**2e:** R_1, R_2,/H, R_3/Br	1.5	14	84



Scheme 3.2 Possible reaction mechanism of **1a** synthesis from **2a**

3.3 EXPERIMENTAL PROCEDURE

3.3.1 Materials and Methods

All reagents were prepared using chemicals obtained from commercial sources and used without further purification. Most of the reactions were performed under aerobic or anaerobic conditions in oven-dried glassware with magnetic stirring. All reactions were monitored by analytical thin layer chromatography (TLC) using Merck pre-coated silica gel glass plates (0.25mm) and spot detected under either I_2 chamber or UV-lamp. The flash column chromatography was carried out over silica gel 60 (230–400 mesh), purchased from Kanto Chemical Co. Inc. Melting points were determined on a Yanagimoto melting point apparatus. FT-IR spectra were recorded on a JASCO FTIR spectrometer 4200; and samples were

prepared as KBr (Sigma Aldrich, USA) plates. NMR spectra were recorded in $CDCl_3$ (Kanto Chemical Co. Inc.) at Varian NMR System 500 (Varian LTD) at 500 MHz for ^1H NMR and 125 MHz for ^{13}C NMR as well. The internal standard for NMR was 0.03% tetramethylsilane (TMS). Chemical shifts (δ) are given in ppm respect to TMS and coupling constants (*J*) are given in Hz. High-resolution mass spectra (HRMS) were acquired on a JMS-700AM (JEOL) and JSM-777V (JEOL) spectrometer using EI (Electron Impact) and FAB (Fast Atom Bombardement) techniques. X-ray diffraction of the single crystals were recorded using CrystalClear (Rigaku/MSC, 2006), CrystalClear, SHELXS2013/1 (Sheldrick, 2008), SHELXL2014/7 (Sheldrick, 2008), Mercury (Macrae et al., 2006), SHELXL2014/7 computer programs.

3.3.2 General Experimental Procedure

3.3.2.1 Reduction of quinone derivatives (1a-g)

At the beginning of the synthetic process, 5% Pd-C (10.0 mg) was charged in a round bottom flask with EtOAc (15.0 ml) in H_2 atmosphere and vigorous stirred for 30 minutes to allow Pd-C adsorbed the H_2 molecules. Then, **1a** (48.0 mg, 0.1 mmol) was added to the reaction vessel and stirred the mixture for the next 48h. Subsequently, the solution was filtered using celite and concentrated in rotary to obtain **2a** as radish yellow solid (99.0% yield).

3.3.2.1.1 *[1,1'-bibenzo[c]phenanthrene]-2,2'-diol (**2a**):* mp.: 270-275°C; FTIR (in KBr): 3297, 3045, 1698, 1488, 1283 and 833cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz, δ/ppm) : δ= 6.65 (2H, t, *J*=7.0 Hz), 6.97 (4H, t, *J*= 8.0 Hz), 7.03 (2H, d, *J*= 8 Hz), 7.09 (4H, t, *J*= 8.0 Hz), 7.23 (2H, d, *J*= 8.5 Hz), 7.29 (2H, d, *J*= 8.0 Hz), 7.38 (2H, d, *J*= 8.5 Hz), 7.45 (2H, d, *J*= 8.5 Hz). ^{13}C NMR ($CDCl_3$, 125 MHz, δ/ppm): δ= 118.15, 120.74, 123.35, 123.61, 124.82, 124.92, 125.02, 125.45, 125.67, 126.15, 127.59, 128.37, 129.83, 130.03, 130.60, 152.21. HRMS (EI) calculated for $C_{36}H_{22}O_2$ $[M]^+$ 486.1619, found 486.1627.

3.3.2.1.2 *3,3'-dimethyl-[1,1'-bibenzo[c]phenanthrene]-2,2'-diol (**2b**):* mp.: 294-296°C; FTIR (in KBr): 3491, 3046, 2910, 1481, 1329, 1152 and 826 cm^{-1}; ^1H-NMR ($CDCl_3$, 500 MHz) : δ=2.68 (3H, s, -Me), 6.58 (1H, t, *J*=7.0 Hz), 6.65 (1H, s), 6.93-6.98 (4H, m), 7.06 (1H, d, *J*=8.0 Hz), 7.19 (1H, d, *J*=8.5 Hz), 7.28 (2H, d, *J*=8.0 Hz), 7.32 (1H, s); ^{13}C NMR ($CDCl_3$, 125 MHz, δ/ppm): δ= 151.42, 130.98, 130.46, 130.31, 130.07, 127.70, 127.04, 126.64,

125.92, 125.79, 125.34, 125.23, 125.18, 123.86, 123.76, 122.25, 119.28, 17.29. HRMS (EI) calculated for $C_{38}H_{26}O_2$ $[M]^+$ 514.1932, found 514.1929.

3.3.2.1.3 *3,3'-diethyl-[1,1'-bibenzo[c]phenanthrene]-2,2'-diol (**2c**):* mp.: 210-215°C; FTIR (in KBr): 3439, 3045, 2964, 1262, 1087 and 802 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 500 MHz) : δ= 1.75 (3H, t, *J*=7.0 Hz), 3.60 (2H, m), 5.73 (1H, t, *J*=7.0 Hz), 6.24 (1H, d, *J*=8.5 Hz), 6.67 (1H, s), 6.75 (1H, t, *J*=7.0 Hz), 7.29 (1H, d, *J*=8.5 Hz), 7.37 (1H, d, *J*=8.5 Hz), 7.51 (1H, d, *J*=8.5 Hz), 7.56 (1H, d, *J*=8.5 Hz), 7.94 (1H, d, *J*=8.5 Hz), 8.08 (1H, s); ^{13}C NMR ($CDCl_3$, 125 MHz, δ/ppm): δ=153.28, 130.04, 129.79, 129.67, 127.44, 126.62, 126.57, 126.19, 125.82, 125.51, 125.36, 125.22, 125.10, 124.92, 124.08, 123.73, 122.59, 122.19, 23.74, 14.48. HRMS (EI) calculated for $C_{40}H_{30}O_2$ $[M]^+$ 542.2245, found 542.2248.

3.3.2.1.4 *3,3'-di-tert-butyl-[1,1'-bibenzo[c]phenanthrene]-2,2'-diol (**2d**):* mp.: >300ºC; FTIR (in KBr): 3445, 2958, 2906, 1232 and 827 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 500 MHz) : δ= 1.96 (9H, s), 5.76 (1H, t, *J*=7.0 Hz), 6.24 (1H, d, *J*=8.5 Hz), 6.77 (1H, t, *J*=7.0 Hz), 7.30 (1H, d, *J*=8.5 Hz), 7.36 (1H, d, *J*=8.5 Hz), 7.49 (1H, d, *J*=8.5 Hz), 7.55 (1H, d, *J*=8.5 Hz), 7.96 (1H, d, *J*=8.5 Hz), 8.14 (1H, s); ^{13}C NMR ($CDCl_3$, 125 MHz, δ/ppm): δ= 152.58, 133.83, 129.73, 129.70, 127.57, 126.64, 126.51, 126.32, 125.62, 125.48, 124.92, 124.17, 124.12, 123.24, 122.23, 121.70, 35.18, 30.87; HRMS (EI) calculated for $C_{44}H_{38}O_2$ $[M]^+$ 598.2871, found

3.3.2.1.5 *6,6'-dibromo-[1,1'-bibenzo[c]phenanthrene]-2,2'-diol (**2e**):* mp.: 262-265°C; FTIR (in KBr): 3491, 3265, 3048 2965, 1590, 1262, 1038 and 799 cm^{-1}; ^{1}H-NMR (DMSO, 500 MHz) : δ= 6.65 (1H, t, *J*=7.0 Hz), 7.05 (1H, t, *J*=7.0 Hz), 7.08 (1H, d, *J*=7.5 Hz), 7.35-7.44 (6H, m); ^{13}C NMR (DMSO, 125 MHz, δ/ppm): δ=116.28, 120.35, 122.13, 123.67, 123.98, 125.19, 125.50, 125.71, 126.95, 127.12, 127.25, 128.00, 128.10, 129.02, 129.05, 129.21, 129.30, 129.72, 155.65; HRMS (EI) calculated for $C_{36}H_{20}Br_2O_2$ $[M]^+$ 641.9830, found 641.9812.

3.3.2.2 Oxidation of BIPOL derivatives (2a-f)

2a (25.0 mg, 0.05 mmol), CuCl(OH)-TMEDA (2.0 mg, 0.005 mmol) were mixed in a round bottom flask with EtOH (5 ml) and stirred the solution at room temperature in open air for 45min. Then, the red precipitate **1a** was collected through filtration and took it ^{1}H NMR. The spectra showed that, the reaction is being preceded quite smoothly without formation any by-products. (19.2 mg, 80% yield).

❖ ***N.B.: Spectroscopic data of 1a-f have already mentioned in Chapter 2.***

3.4 CONCLUSION

In this chapter, I have successfully synthesized and characterized in racemic form (*R/S*) a new class of novel BIPOLs ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) type derivatives **2a-g** using the conventional catalytic process. The BIPOLs ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) derivatives **2a-g** has close resemblance with the BINOL type derivatives and optically active BINOL type derivatives has successfully used in many asymmetric catalysis. Therefore, my strategy offers a feasible methodology for the construction of BIPOLs ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) derivatives **2a-g**. The optical resolution and asymmetric catalytic use of BIPOLs are currently under investigation in my laboratory.

3.5 REFERENCES

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CHAPTER 4

A novel synthesis of halogenated oxa[9]helicenes and dibromo spiro lactone derivative by the reaction of the helical quinones with several halogenating regents

Synopsis

A new class of halogenated oxa[9]helicene derivatives along with dibromo spiro-lactone were synthesized in excellent yields, and the compounds were successfully characterized by different spectroscopic techniques (e.g. ^{1}H and ^{13}C NMR, HRMS spectroscopy and X-ray crystallography). I also proposed a tentative reaction mechanism of halogenation reactions and dibromo spiro lactone formation reaction as well.

CHAPTER 4

4.1 INTRODUCTION

Helicenes and helicene like molecules are known for more than 100 years. In the year of 1903, the first diaza[5]helicene (3,4-diazadibenzo[*c*,*g*]phenanthrene), was prepared.[1] After 10 years, [4]helicene (benzo[*c*]phenanthrene) was reported as the first carbohelicene.[2] Until now, many research works have been published on carbohelicenes,[3] azahelicenes[4] and thiahelicenes.[5] However, in the case of oxa[n]helicene where a furan ring embeds into a helicene framework have not been well-convoluted compare to the other heterohelicenes and only a few research works[6] have been found in literature.

Recently, we have reported the synthesis of oxa[9]helicene derivativeswhich are composed of eight benzene rings and one furan ring. The reaction of helicalquinones with several nucleophiles such as Lawesson's reagent,[7] phosphorus pentasulfide,[7] alcohols[8] and thiols[9]gave a variety of functionalized and non-functionalized oxa[9]helicenes. The starting helical quinone derivatives are available by oxidative coupling reaction of 2-hydroxybenzo[*c*]phenethrenesusing copper-diamine complexes.[10, 11, 12]

With this background, our research initially focused on synthesis of halo-substituted oxa[9]helicenes by the reaction of the helical quinones with various halogenating reagents. Haloaryl compounds are commonly used for many types of cross-coupling reactions such as Suzuki-Miyaura, Mizoroki-Heck, Sonogashira etc. Thus, this halo-substituted oxa[9]helicene could be easily introduced many types of substituents for oxa[9]helicenes. Most recently, we have successfully applied some of amphiphilic oxa[9]helicene derivatives in Langmuir film formation[13,14] because they have shown fascinating optical properties. The newly synthesized 9-halo-11-oxa[9]helicene derivatives might extend the formation of new functionalized amphiphilic oxa[9]helicene compounds and improve the optical properties as well.

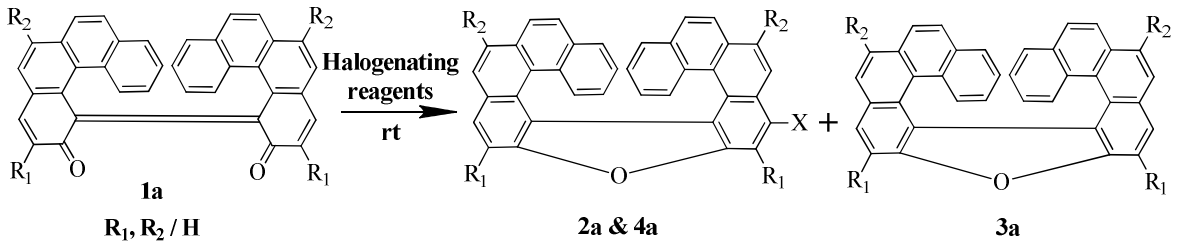
In such a reason, we tried to figure out the optimal conditions for the synthesis of halo-substituted oxa[9]helicene derivatives. Advancing this procedure, we found the formation of dibromo-substituted spiro lactone derivative by the reaction of helical quinone with some brominating regents.

In this paper work shows the regioselective synthesis of 9-halo-substituted oxa[9]helicene derivatives and dibromo spiro lactone compound from helical quinones.

4.2 RESULTS AND DISCUSSION

The helical quinone derivatives**1a-d**, which are synthesized by oxidative coupling reaction of 2-hydroxybenzo[*c*]phenanthrenes were subjected to halogenations reactions with several halogenating reagents to obtain halo substituted oxa[9]helicenes derivatives. oxa[9]helicenes which contain eight *ortho*-condensed benzene ring and a furan ring. When various halogenating reagents react with quinones **1a-d** the halide ion act as a nucleophile and substituted regioselectively at 9th position of the adjacent benzene of the furan ring.At the beginning of the investigation, we appliedvarious halogenating reagents to figure out the best reagent for our reactions. Therefore, initially we used only non-substituted quinone **1a**as our sole starting material and conducted a series of reactions at different conditions and with different reagents (Table 4.1).

Table 4.1 Synthesis of 9-halo-11-oxa[9]helicenes



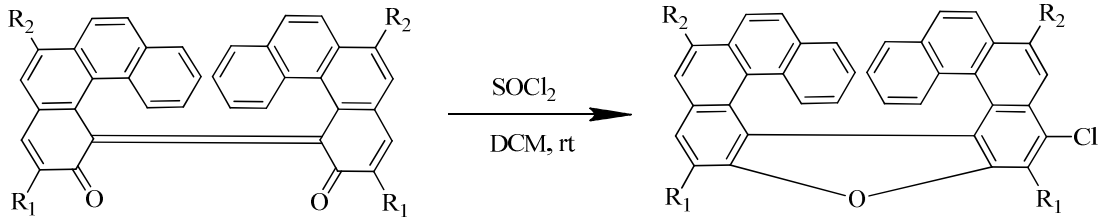
Entry[a]	Reagent/ (equiv)	Solvent	Acid/ (equiv)	Time/ h	Product /X	Yield(%)[b] (**2a** or **4a** : **3a**)
1	HCl (4)	AcOH	-	24	**2a**/Cl	82
2	PCl_5 (3)	$CHCl_3$	-	3.5	**2a**/Cl	88
3	**$SOCl_2$ (4)**	**$CHCl_3$**	**-**	**0.5**	**2a/Cl**	**95**
4	$(COCl)_2$ (2)	$CHCl_3$	-	3	**2a**/Cl	67
5	**$SOBr_2$ (4)**	**$CHCl_3$**	**-**	**1.5**	**4a/Br, 3a**	**80(4:1)**
6	HBr (3)	AcOH	-	24	**4a**/Br, **3a**	63 (1:1)
7	PBr_3 (3)	$CHCl_3$	-	1.5	**4a**/Br, **3a**	39 (1:1)
8	TBAB (3)	$CHCl_3$	*p*TSA (1)	24	**4a**/Br, **3a**	18 (1:2)
9	PBr_5 (3)	$CHCl_3$	-	5	**4a**/Br, **3a**	18 (1:1)

10	HI (3)	AcOH	-	24	**3a**	88
11	HF (3)	AcOH	-	24	-	-
12	TBAF (3)	AcOH	-	24	-	-

[a]All reactions were carried out at room temperature.
[b]Isolated yield.

When HCl used as a nucleophile in acetic acid with helical quinone **1a**at room temperature, chloro substituted oxa[9]helicene **2a** (Table 4.1, entry 1) was obtained. Phosphorus pentachloride (PCl_5), thionyl chloride ($SOCl_2$) and oxalylchloride [$(COCl)_2$] in chloroform also gave the same product selectively with helical quinone**1a** (Table 4.1, entries 2-4).However, in the case of bromide, bromo substituted oxa[9]helicene **4a** and non-substituted oxa[9]helicene **3a** were produced as various ratios (Table 4.1, entries 5-9). On the other hand, hydrogen iodide presented non-substitutedoxa[9]helicene**3a** selectively in good yield (entry 10). Nevertheless, fluorination reaction did not proceed at all (Table 4.1, entries 11-12). After sort out the best halogenationg reagents from the investigation, we used thionyl chloride and thionyl bromide for other quinone derivatives **1b-d**. For chloro substituted oxa[9]helicene derivatives **2a-d** we obtained very good to excellent yields (Table 4.2).

Table 4.2 Synthesis of 9-chloro-11-oxa[9]helicenes **2a-d**



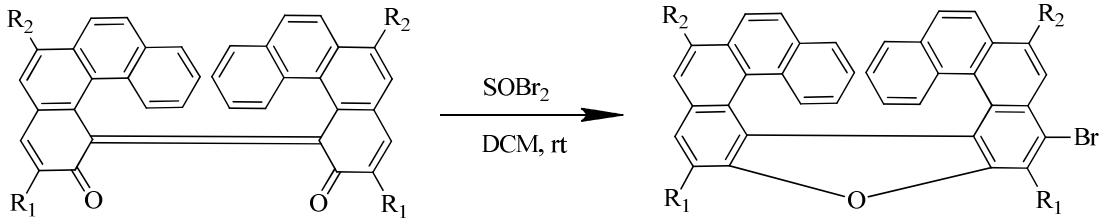
1a-d **2a-d**

Entry[a]	Substrate	Substituents	$SOCl_2$/ (equiv)	Time/h	Product	Yield of **2** (%)[b]
1	**1a**	R^1, R^2= H	4	0.5	**2a**	95
2	**1b**	R^1=Me, R^2=H	6	2 days	**2b**	85
3	**1c**	R^1=Et, R^2=H	4	2 days	**2c**	86
4	**1d**	R^1=H, R^2=Br	4	1	**2d**	91

[a]All reactions were carried out at room temperature.
[b]Isolated yield by flash column chromatography.

On the other hand, in the cases of bromination reaction, mixtures of substituted and non-substituted products were obtained (Table 4.3).

Table 4.3 Synthesis of 9-bromo-11-oxa[9]helicenes **4a-d**



1a-d **4a-d**

Entry[a]	Substrate	Substituents	$SOBr_2$/ (equiv)	Time / h	Product	Yield of **4** (%)[b] (**4**: **3**)
1	**1a**	R^1, R^2= H	4	2	**4a**	80 (4 : 1)
2	**1b**	R^1=Me, R^2=H	4	46	**4b**	-
3	**1c**	R^1=Et, R^2=H	4	48	**4c**	-
4	**1d**	R^1=H, R^2=Br	4	1	**4d**	83(3 : 1)

[a]All reactions were carried out at room temperature.
[b]Isolated yield by flash column chromatography.

In the ^{1}H NMR spectra, the singlet peak for H_{10} proton of **2a** depicted at 7.68 ppm but for **4a** the corresponding proton singlet peak appeared at 8.60 ppm (Figure 4.1). Although chlorine has more electron withdrawing ability than bromine but magnetic anisotropic effect of bromine is much higher compare to chlorine.

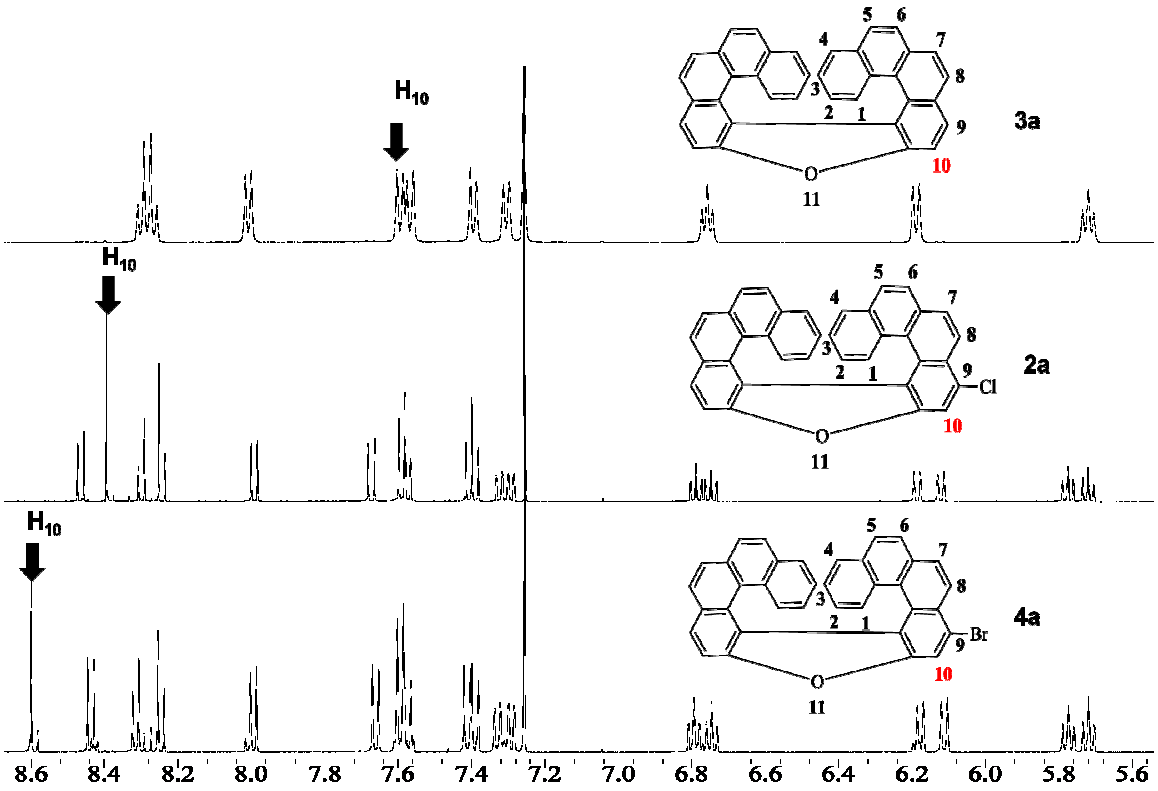
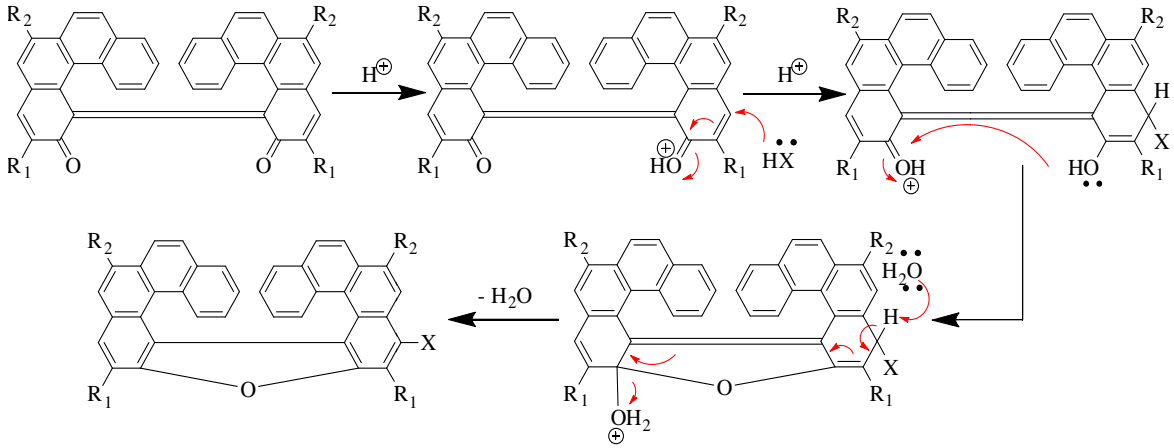


Figure 4.1 Comparative ^{1}H NMR spectra of **2a** and **4a** with **3a**

The halogenations reaction might follow the reaction mechanism as shown in scheme 3.1. The reaction proceeded by conjugate addition by halide ion. Later, the intermediate unstable molecules might be going through intramolecular cyclization along with deprotonation and dehydration.



Scheme 4.1 Tentative reaction mechanism of halogenations of quinone derivatives

When we used NBS (*N*-bromosuccinimide) for bromination reaction with quinone **1a**, 9-bromo oxa[9]helicene **2a** was not obtained. X-ray crystal structure of the product **5** revealed as dibromo substituted spiro lactone compound (Figure 4.2). Single-crystal X-ray analysis of **5** established that, the compound was crystallized in the triclinic *P1* space group; their unit cell consists of two molecules one is "*P*" conformation and the other in "*M*" conformation. This indicates the absence of any other spontaneous resolution, this type of phenomenon occasionally observed in some helical molecules during crystallization.[15]

Crystal structure is packed in alternative *P* and *M* along each channel (Figure 4.3). The dihedral angle or torsional angle of C5-C1-C20-C21 was obtained -61.2 º. Compare to other helical compounds (Chapter 2, Figure 2.1) this value is much higher. The reason might be, in spiro lactone compound **5**, two moieties are connected at C-20 position which is sp^3 hybridized and the rings get more freedom to rotate. The negative sign means that, two moieties are oriented in anti-clockwise direction. The anti-clockwise rotation of the rings occurred due to the lactone oxygen at C-18 and C-19 position. This negative value also defines that, the crystal data are for *M* isomer of **5.**

In previous X-ray structure at chapter 2 we can see that, in case of all inner carbon atoms shows the same sign of torsional angle, but in case of spiro lactone **5**, the torsional angle of C6-C5-C1-C20 is found -83.5 º, this value is much higher than the other inner torsional angle values and opposite in sign (Table 4.4).

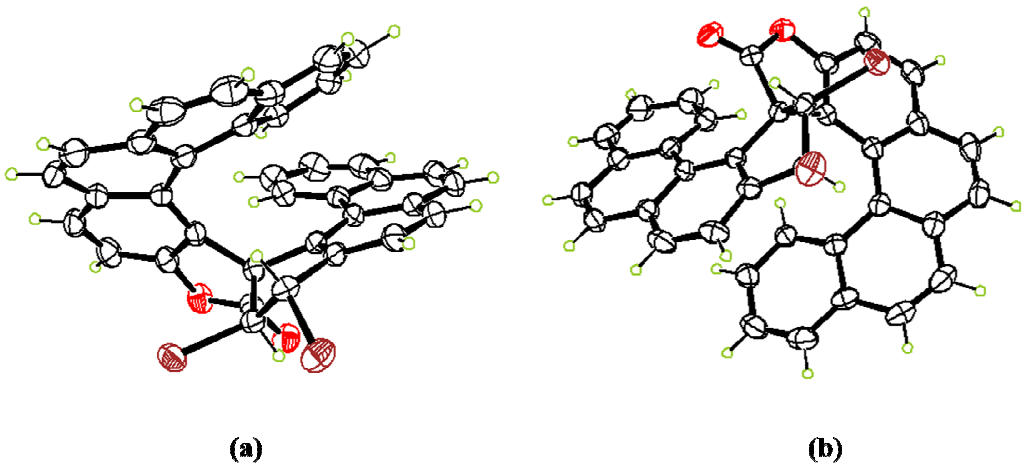


Figure 4.2 ORTEP drawing of **5**, (a) side view and (b) top view with ellipsoids at 30% probability.

Table 4.4 Selective dihedral angle (°) of **5**

C-C bonds	Dihedral angle (°)
C11–C10–C6–C5	12.3
C10–C6–C5–C1	12.6
C6–C5–C1–C20	**-83.4**
C5–C1–C20–C21	**-61.2**
C1–C20–C21–C25	26.9
C20–C21–C25–C26	34.8
C21–C25–C26–C27	18.6

The torsional angles of the inner carbon atoms at Table 4.4 suggesting different degrees of distortion in the aromatic rings. The bond length in the skeleton is also different. In comparison of the standard bond length of benzene (1.39 Å),[16] the range of C-C bond lengths of the inner helix was observed 1.405-1.456 Å, while the same on the outer periphery was shorter, as seen in the range of 1.322-1.366 Å (Table 4.5) clearly due to the much greater strain exerted in the inner carbon bonds.

Table 4.5 Selective inner and outer C-C bond length (Å) of **5**

Entry	Inner Carbon	Bond length / Å	Outer Carbon	Bond length / Å
1	C26-C27	1.405	C29-C30	1.366
2	C25-C26	1.455	C32-C33	1.322
3	C25-C21	1.447	C35-C36	1.339
4	C21-C20	1.429	C23-C24	1.351
5	C5-C6	1.432	C13-C14	1.350
6	C6-C10	1.456	C16-C17	1.332
7	C10-C11	1.408	C8-C9	1.369

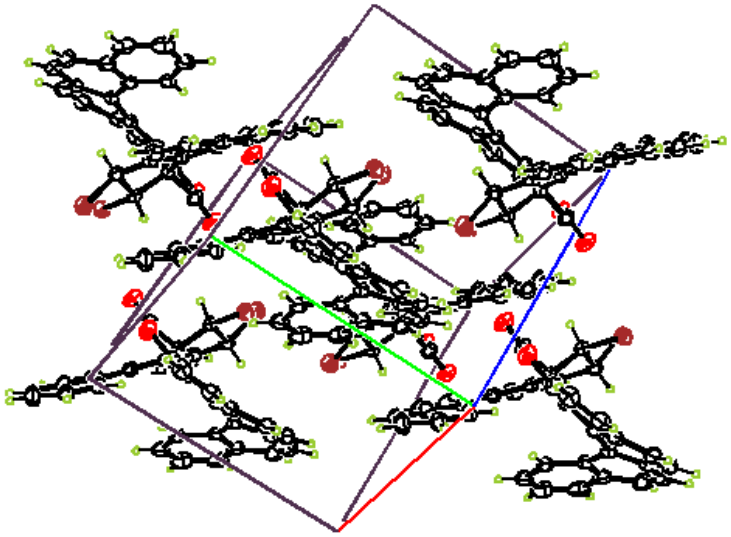
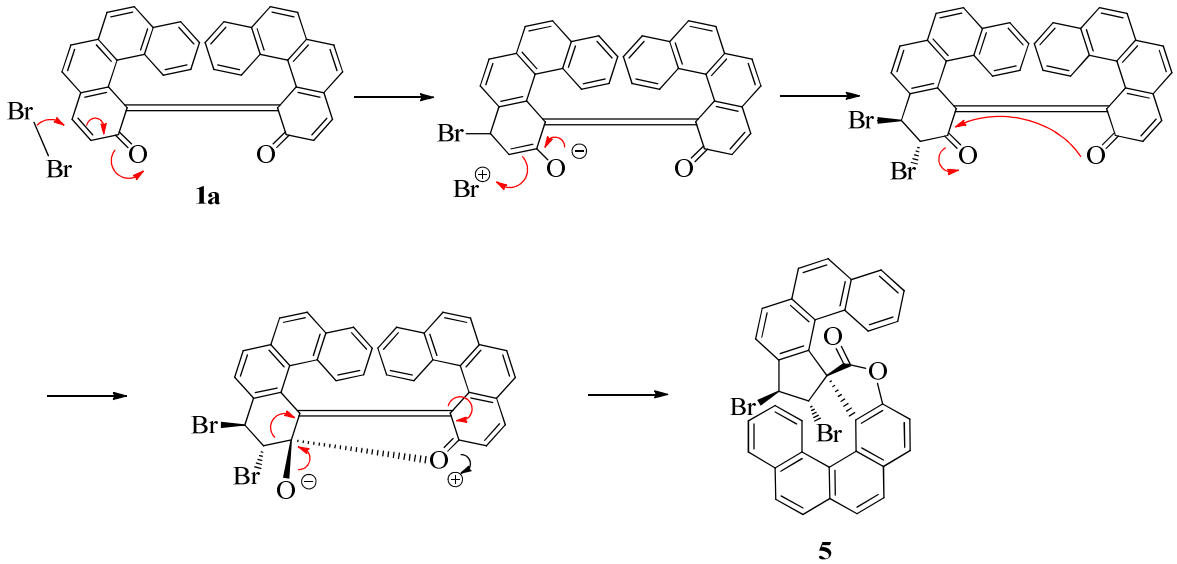


Figure 4.3 Unit cells of **5** with ellipsoids at 30% probability

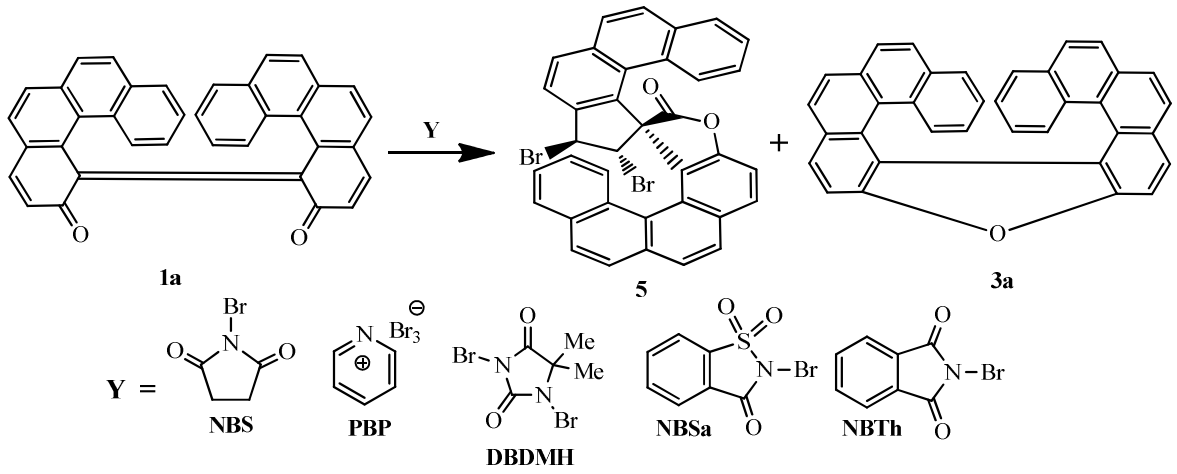
After analyzing the X-ray structure of **5,** the bromine is added to one of the five membered ring (another five membered ring is lactone) in trans-form. In this reaction, initially NBS forms Br_2 molecule in low concentration. Initially, a Michael type addition of bromine to **1a** proceeded; the α,β-dibromo-substituted carbonyl group became more reactive by electron-withdrawing bromine atoms. The nucleophilic cyclization by opposite carbonyl oxygen proceeded more easily. This reaction step may be triggered the following rearrangement reaction to form spiro lactone derivative (Scheme 4.2).



Scheme 4.2 Tentative reaction mechanism of **5** (Michael addition type reaction).

The same reaction was also possible for other brominating reagents (Table 4.6). Nevertheless, in the case of NBS gave good results. Even though in the cases of NBS, other quinone derivatives **1b-d** did not give dibromo-spiro lactone derivatives at all. The reason is quite unknown to us and we are trying to figure out the fact behind this phenomenon.

Table 4.6 Synthesis of dibromo spiro lactone (**5)** using various brominating reagents



Entry[a]	Reagents(equiv)	solvent	Time (h)	Yield (%)[b]	Ratio (**5:3a**)[c]
1	NBS (2)	DCE	9	**5** (66)	-
2	NBS (2)	DCE	24	**5** (97)	-
3	PBP (3)	DCE	2days	-	-
4	DBDMH(2)	$CHCl_3$	24	**5** and **3** (40)	(1: 4)
5	DBDMH(4)	$CHCl_3$	7days	**5** and **3** (58)	(1: 1)
6	BBr_3(10)	DCM	19	**5** and **3** (34)	(1: 1)
7	NBSa (2)	DCM	13	-	-
8	NBTh(2)	$CHCl_3$	68	**5** (100)	-
9	Br_2 (3)	$CHCl_3$	18	-	-

[a]All reactions were carried out at room temperature.
[b]Isolated and combined yield.
[c]The product ratio was determined from crude ^{1}H NMR spectra.

4.3 EXPERIMENTAL PROCEDURE

4.3.1 Materials and Methods

All reagents were prepared using chemicals obtained from commercial sources and used without further purification. Most of the reactions were performed under aerobic or anaerobic conditions in oven-dried glassware with magnetic stirring. All reactions were monitored by analytical thin layer chromatography (TLC) using Merck pre-coated silica gel glass plates (0.25mm) and spot detected under either I_2 chamber or UV-lamp. The flash column chromatography was carried out over silica gel 60 (230–400 mesh), purchased from Kanto Chemical Co. Inc. Melting points were determined on a Yanagimoto melting point apparatus. NMR spectra were recorded in $CDCl_3$ (Kanto Chemical Co. Inc.) at Varian NMR System 500 (Varian LTD) at 500 MHz for ^1H NMR and 125 MHz for ^{13}C NMR as well. The internal standard for NMR was 0.03% tetramethylsilane (TMS). Chemical shifts (δ) are given in ppm respect to TMS and coupling constants (*J*) are given in Hz. High-resolution mass spectra (HRMS) were acquired on a JMS-700AM (JEOL) and JSM-777V (JEOL) spectrometer using FAB (Fast Atom Bombardment) and EI (Electron Impact) techniques.

X-ray diffraction of the single crystals were recorded using CrystalClear (Rigaku/MSC, 2006), CrystalClear, SHELXS2013/1 (Sheldrick, 2008), SHELXL2014/7 (Sheldrick, 2008), Mercury (Macrae et al., 2006), SHELXL2014/7 computer programs.

4.3.2 General Experimental Procedure

4.3.2.1 General procedure for the synthesis of 9-chloro-11-oxa[9]helicenes (2a-d)

1a (48 mg, 0.1 mmol) was added with $SOCl_2$ (4 equiv.) in DCE and gently stirred at room temperature for 30 minutes. The mixture was concentrated under vacuum and the crude product was purified by flash column chromatography on silica gel where chloroform used as mobile phase. Eventually, light yellow crystal of **2a** was obtained with excellent yield (99%).

3.3.2.1.1 *9-Chloro-11-oxa[9]helicene (**2a**) :* Light yellow crystal, mp.: 275-280ºC. ^1H NMR (500 MHz, $CDCl_3$, δ/ppm): 8.47 (1H, d, *J*=8.5 Hz); 8.40 (1H, s); 8.30 (1H, d, *J*=9.0 Hz);

8.25 (1H, d, *J*=8.5 Hz); 8.00 (1H, d, *J*=8.0 Hz); 7.68 (1H, d, *J*=9.0 Hz); 7.60-7.57 (3H, m); 7.42-7.39 (2H, m); 7.33 (1H, d, *J*=8.0 Hz); 7.29 (1H, d, *J*=7.5 Hz); 6.79 (1H, t, *J*=8.0 Hz); 6.75 (1H, t, *J*=8.0 Hz); 6.19 (1H, d, *J*=8.0 Hz); 6.12 (1H, d, *J*=8.5 Hz); 5.75 (1H, t, *J*=7.0 Hz); 5.72 (1H, t, *J*=8.0 Hz). ^{13}C NMR (125 MHz, $CDCl_3$, δ/ppm): 154.64, 153.25, 131.10, 130.30, 130.27, 129.88, 129.85, 129.82, 128.24, 127.85, 127.45, 127.35, 127.31, 126.90, 126.85, 126.82, 126.59, 126.54, 126.27, 126.24, 125.74, 125.58, 125.49, 125.29, 124.96, 124.60, 124.49, 124.44, 124.39, 122.70, 122.67, 122.50, 120.90, 120.58, 111.96, 111.18. HRMS (EI) calcd for $C_{36}H_{19}ClO$ $[M]^+$ 502.1125 found 502.1113.

4.3.2.1.2 *9-Chloro-10, 10'-dimethyl-11-oxa[9]helicene (**2b**) :* Light yellow crystal, mp.: >300ºC. ^{1}H NMR (500 MHz, $CDCl_3$, δ/ppm): 8.49 (1H, d, *J*=8.5 Hz); 8.07 (1H, s); 7.92 (1H, d, *J*=8.5 Hz); 7.64 (1H, d, *J*=9.0 Hz); 7.54-7.51 (3H, m); 7.38 (1H, d, *J*=9.0 Hz); 7.35 (1H, d, *J*=9.0 Hz); 7.31 (1H, d, *J*=8.0 Hz); 7.28 (1H, d, *J*=7.5 Hz); 6.79 (1H, t, *J*=8.0 Hz); 6.74 (1H, t, *J*=8.0 Hz); 6.23 (1H, d, *J*=8.5 Hz); 6.17 (1H, d, *J*=8.0 Hz); 5.77 (1H, t, *J*=7.0 Hz); 5.72 (1H, t, *J*=7.0 Hz); 3.20 (3H, s); 3.16 (3H, s). ^{13}C NMR ($CDCl_3$, 125 MHz, δ/ppm): δ = 153.84, 152.91, 130.39, 130.05, 129.87, 129.85, 129.73, 129.65, 127.98, 127.50, 127.40, 127.33, 127.26, 126.79, 126.75, 126.67, 126.39, 126.30, 126.29, 126.06, 125.60, 125.58, 125.38, 125.01, 124.63, 124.32, 124.30, 123.82, 123.08, 122.60, 122.49, 122.47, 121.40, 120.93, 120.29, 119.96, 16.08, 14.24. HRMS (FAB) calcd for $C_{38}H_{23}ClO$ $[M]^+$ 530.1437 found 530.1436.

4.3.2.1.3 *9-Chloro-10, 10'-diethyl-11-oxa[9]helicene (**2c**) :* Light yellow crystal, Light yellow crystal, mp.: 242-245ºC. ^{1}H NMR (500 MHz, $CDCl_3$, δ/ppm): 8.51 (1H, d, *J*=8.5 Hz); 8.08 (1H, s); 7.93 (1H, d, *J*=8.5 Hz); 7.64 (1H, d, *J*=9.0 Hz); 7.56-7.51 (3H, m); 7.38 (1H, d, *J*=9.0 Hz); 7.35 (1H, d, *J*=9.0 Hz); 7.30 (1H, d, *J*=8.0 Hz); 7.27 (1H, d, *J*=7.5 Hz); 6.78 (1H, t, *J*=8.0 Hz); 6.73 (1H, t, *J*=8.0 Hz); 6.25 (1H, d, *J*=8.5 Hz); 6.19 (1H, d, *J*=8.0 Hz); 5.77 (1H, t, *J*=7.0 Hz); 5.72 (1H, t, *J*=7.0 Hz); 3.60 (4H, m); 1.74 (3H, t, *J*=7.5 Hz); 1.70 (3H, t, *J*=7.5 Hz). ^{13}C NMR ($CDCl_3$, 125 MHz, δ/ppm): δ = 153.41, 152.49, 130.13, 129.87, 129.85, 129.76, 129.67, 129.64, 127.53, 127.43, 127.37, 127.34, 126.78, 126.75, 126.67, 126.49, 126.33, 126.31, 126.28, 126.25, 126.23, 125.98, 125.63, 125.52, 125.38, 125.03, 124.64, 124.30, 124.29, 124.02, 123.09, 122.73, 122.46, 122.44, 120.98, 120.17, 23.73, 22.42, 14.48, 14.22. HRMS (FAB) calcd for $C_{40}H_{27}ClO$ $[M]^+$ 558.1750 found 558.1724.

4.3.2.1.4 *7, 7'-Dibromo-9-Chloro-11-oxa[9]helicene (**2d**) :* Light yellow crystal, mp.: >300ºC. ^{1}H NMR (500 MHz, $CDCl_3$, δ/ppm): 8.77 (1H, s); 8.37 (1H, s); 8.30 (1H, s); 8.24 (1H, d, *J*=8.5 Hz); 8.20 (1H, d, *J*=8.5 Hz); 7.91 (1H, d, *J*=9.0 Hz); 7.87 (1H, d, *J*=9.0 Hz); 7.69 (1H, d, *J*=8.0 Hz); 7.65 (1H, d, *J*=9.0 Hz); 7.39 (1H, d, *J*=7.5 Hz); 7.35 (1H, d, *J*=8.0 Hz); 6.91 (1H, t, *J*=8.0 Hz); 6.88 (1H, t, *J*=8.0 Hz); 6.15 (1H, d, *J*=8.5 Hz); 6.08 (1H, d, *J*=8.0 Hz); 5.85 (1H, t, *J*=7.0 Hz); 5.78 (1H, t, *J*=7.0 Hz). e^{13}C NMR ($CDCl_3$, 125 MHz, δ/ppm): *δ* = 154.78, 153.44, 130.34, 129.89, 129.77, 129.71, 129.70, 128.75, 128.43, 128.29, 128.22, 127.54, 127.34, 127.30, 127.14, 127.06, 126.91, 126.52, 126.45, 126.22, 125.87, 125.67, 125.25, 125.26, 124.59, 123.63, 123.45, 123.36, 123.25, 123.18, 121.59, 120.84, 120.46, 120.11, 112.71, 112.10. HRMS (FAB) calcd for $C_{36}H_{17}Br_2ClO$ $[M]^+$ 657.9334 found 657.9332.

4.3.2.2 General procedure for the synthesis of 9-bromo-11-oxa[9]helicenes (4a-d)

1a (48 mg, 0.1 mmol) was added with $SOBr_2$ (4 equiv.) in DCE and gently stirred at room temperature for 30 minutes. The mixture was concentrated under vacuum and the crude product was purified by flash column chromatography on silica gel where chloroform used as mobile phase. Eventually, light yellow crystal of **4a** was obtained with good yield (80%).

4.3.2.2.1 *9-Bromo-11-oxa[9]helicene (**4a**) :* Light yellow crystal, mp.: 257-259ºC. ^{1}H NMR (500 MHz, $CDCl_3$, δ/ppm): *δ* = 8.60 (1H, s), 8.43 (1H, d, *J*=8.5 Hz), 8.30 (1H, d, *J*=8.0 Hz), 8.24 (1H, d, *J*=8.5 Hz), 7.99 (1H, d, *J*=8.0 Hz), 7.65 (1H, d, *J*=8.5 Hz), 7.60-7.56 (3H, m), 7.41-7.37 (2H, m), 7.32 (1H, d, *J*=8.0 Hz), 7.28 (1H, d, *J*=7.5 Hz), 6.79 (1H, t, *J*=8.0 Hz), 6.74 (1H, t, *J*=8.0 Hz), 6.17 (1H, d, *J*=8.5 Hz), 6.11 (1H, d, *J*=8.5 Hz), 5.77 (1H, t, *J*=8.0 Hz), 5.72 (1H, t, *J*=8.0 Hz).^{13}C NMR (125 MHz, $CDCl_3$, δ/ppm): *δ* = 154.57, 153.48, 130.31,130.22 129.88, 129.85, 129.82, 128.41, 127.89, 127.44, 127.33, 127.31, 126.99, 126.90, 126.82, 126.81, 126.53, 126.22, 126.19, 125.75, 125.72, 125.48, 125.28, 125.27, 124.94, 124.54, 124.49, 124.46, 124.41, 122.73, 122.69, 121.48, 121.14, 120.90, 115.41, 111.21. HRMS (EI) calcd for $C_{36}H_{19}BrO$ $[M]^+$ 546.0619 found 546.0616.

4.3.2.3 Synthesis of dibromo spiro lactone (5)

1a (49 mg, 0.1 mmol) was added with N-Bromosuccinamide (0.0355 gm, 0.2mmol) in DCE at room temperature for 24 h. The mixture was concentrated under vacuum and the crude

product was purified by flash column chromatography on silica gel where $CHCl_3$ used as a mobile phase to obtain pure **5** as yellow crystal with excellent yield (97%).

Yellow crystal, mp.: 196-198ºC. ^{1}H NMR (500 MHz, $CDCl_3$, δ/ppm): δ = 8.98 (1H, d, *J*=8.5 Hz); 8.22 (1H, d, *J*=8.5 Hz); 8.05 (1H, dd, *J*=2, 7.5 Hz); 7.94-7.71(11H,m); 7.51 (1H, d, *J*=8.0 Hz); 7.03 (1H, d, *J*=8.5 Hz); 6.73 (1H, t, *J*=6.0 Hz); 5.26 (1H, t, *J*=7.5 Hz); 4.38 (1H, d, *J*=10.0 Hz); 4.01 (1H, d, *J* = 10 Hz). ^{13}C NMR (125 MHz, $CDCl_3$, δ /ppm) : δ = 56.57, 67.36, 67.98, 113.37, 124.22, 124.78, 125.64, 125.75, 125.76, 126.01, 126.23, 126.33, 126.49, 126.59, 127.44, 127.92, 128.03, 128.31, 128.76, 128.82, 129.08, 129.43, 130.04, 130.19, 130.74, 131.08, 132.05, 132.26, 132.42, 133.30, 133.66, 133.86, 135.47, 142.43, 153.80, 175.23. HRMS (EI) calcd for $C_{36}H_{20}Br_2O_2$ $[M]^+$ 641.9830 found 641.9819.

4.4 CONCLUSION

In this chapter, I have successfully synthesized and characterized a new series of 9-halo-11-oxa[9]helicene derivatives **2a-d** and **4a**. I have also fortuitously synthesized a novel dibromo spiro lactone **5** and successfully figure out its molecular structure. Halo substituted compounds are extensively used in different types of coupling reactions. I hope that my compounds will be able to use in different short of coupling reactions. Currently I am working on it. I am also interested to use dibromo spiro lactone in practical field.

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CHAPTER 5

Synthesis, enantiomeric resolution and optical properties of amphiphilic oxa[9]helicene derivatives

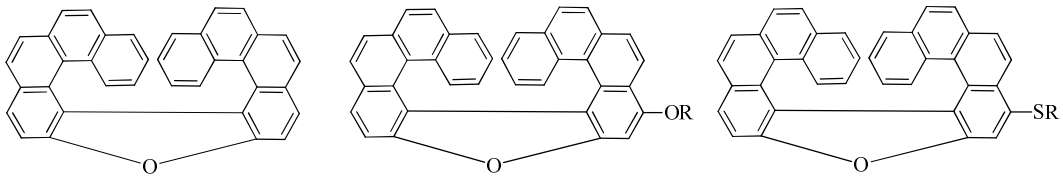
Synopsis

A new class of amphiphilic oxa[9]helicene derivatives were synthesized in good yields, and successfully characterized by different analytical techniques (e.g. ,FT-IR, ^{1}H and ^{13}C NMR spectroscopies, and mass spectroscopy). The compounds are enantiomerically separated by chiral HPLC and absolute configurations of the enantiomers are confirmed by circular dichroism (CD) spectroscopy. Other optical properties (e.g. UV, Photoluminescence and Specific Optical Rotation, Molecular Optical Rotation) of the newly synthesized compounds were also examined as well.

CHAPTER 5

5.1 INTRODUCTION

Helicenes are polycyclic aromatic compounds in which benzene rings are fused in ortho position. After increasing the number of *ortho*- fused aromatic rings (normally, $n > 4$), these molecules adopt a helical conformation to avoid overlapping of the terminal aromatic nuclei and minimizing the internal strain resulting a nonplanar screw-shaped structure. Although helicenes do not have any chiral centers but they show axial chirality. Helicene's chirality arises from the steric hindrance between the terminal rings, which secure the helical structure either the clockwise and anticlockwise direction.[1] Each isomer can be segregated due to their thermal stability and immutable helical skeleton. The twisted nonplanar π-electron systems of helicene molecules show unique properties which are directly associated with their structure, such as large optical rotation and strong circular dichroism (CD).[2] In general, there are two types of helical molecules: one is carbohelicenes and another one is heterohelicenes. Although, early research work on helical molecules was mainly focused on the former class, but recently, more properties that are interesting have been observed for the later type of helical molecules, which contain one or more heteroatoms. Polycyclic aromatic oxygen-containing molecules, especially fused furan ring are expected to provide relatively high HOMO levels.[3] This unique feature is highly attracted the researcher's attention for further improvement in many fields of material sciences including organic light emitting diode (OLED) materials,[4] asymmetric catalysis,[5] chiral molecular recognition,[6] molecular mechines,[7] liquid crystals[8] and so on.



(a) (b) (c)

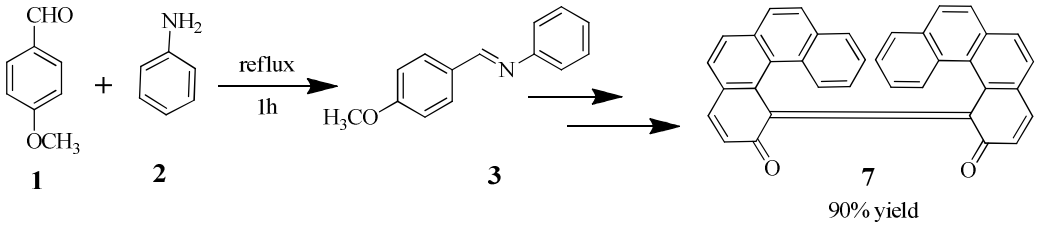
Figure 5.1 Examples of oxa[9]helicene and its derivatives.[12,13,14]

Previously, our research group have been reported the synthesis of a helical shaped quinone derivative which was synthesized by oxidative coupling of 2-hydroxybenzo[*c*]phenanthrene.[9] In chapter 2, I have successfully extended the method for the synthesis of substituted quinone derivatives.[10] Our research group have also been reported the asymmetric synthesis of helical quinone derivatives by using chiral diamine-copper complexes,[11] a novel synthesis of oxa[9]helicenes utilizing the reaction of helical quinones with Lawesson's reagent and phosphorus pentasulfide,[12] aliphatic alcohols,[13] and thiols[14] (Figure 5.1).

In continuation of my research work on the synthesis and study of helicene like molecules and oxa[n]helicenes, in this chapter, I illustrate an easy synthetic way for the synthesis of 9-hydroxy-11-oxa[9]helicene (**9**), 9-ethyleneglycoxy-11-oxa[9]helicene (**10**), 9-triethyleneglycoxy-11-oxa[9]helicene (**11**) and 9-hexaethyleneglycoxy-11-oxa[9]helicene (**12**) from the sole starting material helical quinone (**7**) and try to separate the optical isomers of each final product. I also investigate the optical properties of the compounds as well.

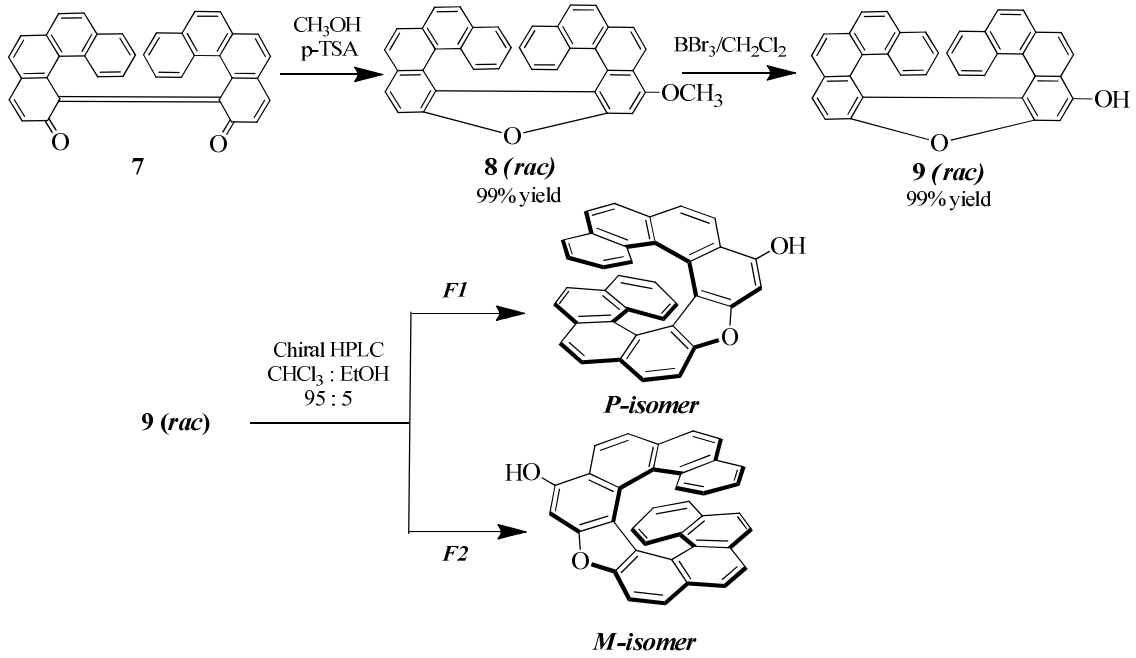
5.2 RESULTS AND DISCUSSION

The commercially available starting chemicals aniline (**1**) and 4-methoxy benzaldehyde (**2**) were mixed in a round bottom flask for 1 h and we obtained the condensed product (*E*)-N-(4-methoxybenzylidene) benzamine (**3**) in excellent yield (99%). The product (**3**) was then subjected to the next reaction, which is known as Siegrist reaction for the formation of corresponding stilbene (**4**). Later, the stilbene (**4**) was irradiated in cyclohexane with a 450W high pressure mercury lamp, on a 10 mmol scale per 1.4 liter of cyclohexane in the presence of stoichiometric amount of iodine as an oxidizing agent and an excess amount of propylene oxide (5-35 ml) as a hydrogen iodide hunter for about 8 h.[15] The expected 2-methoxybenzo[*c*]phenanthrene (**5**) compound introduced into the next demethylation reaction gave corresponding 2-hydroxy benzo[*c*]phenanthrene (**6**). Next the 2-hydroxy benzo[*c*]phenanthrene (**6**) was subjected for oxidative homocoupling reaction with routinely used catalyst system of CuCl(OH)-TMEDA[16] in ethanol at room temperature an aerobic conditions to obtain the sole starting material quinone (**7**) in excellent yield (Scheme 5.1).[10]



Scheme 5.1 Preparation of quinone (7).[10]

Having obtained the key starting material (**7**) we then synthesized 9-hydroxy-11-oxa[9]helicene (**9**).

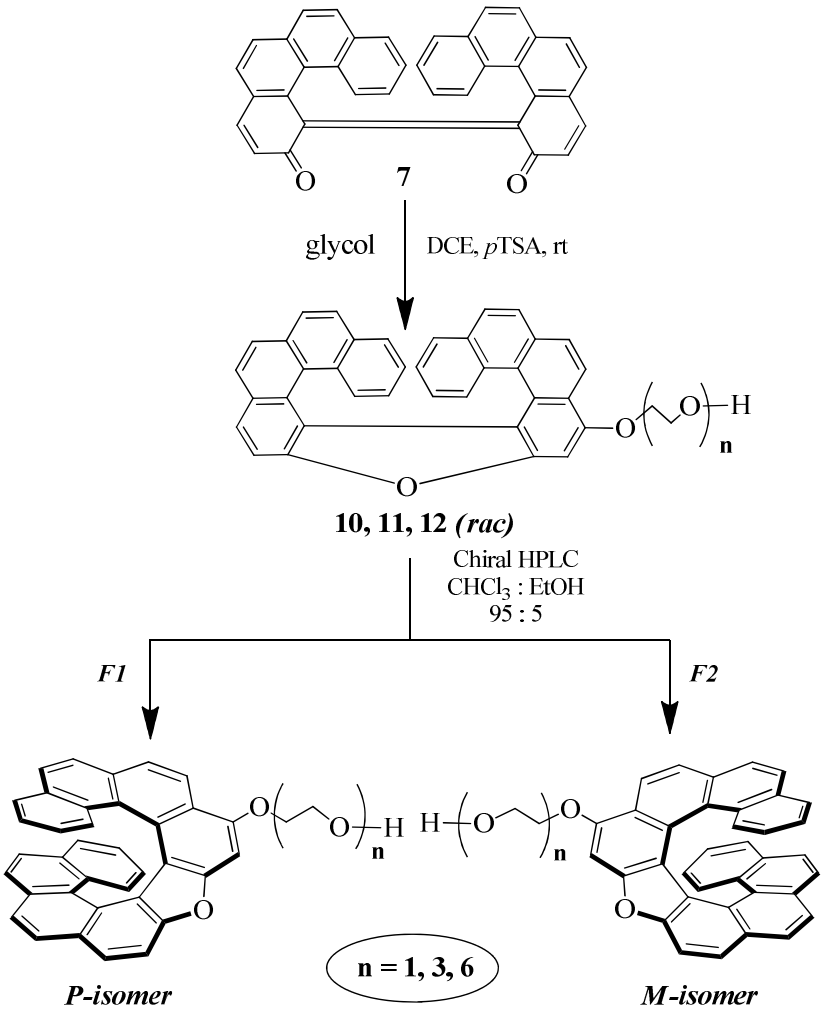


Scheme 5.2 Preparation and optical resolution of **9**

First quinone was added with anhydrous methanol in dichloromethane in presence of *p*TSA at room temperature for about 0.5 h. Later, the mixture was concentrated under vacuum. Finally, the crude product was purified by column chromatography on silica gel (eluent: chloroform) to obtain 9-methoxy-11-oxa[9]helicene (**8**) in excellent yield (99%). Later, the 9-Methoxy-11-oxa[9]helicene (**8**) and BBr_3 /CH_2Cl_2 were charged in a round bottom flask. The reaction mixture was allowed to gentle stirring at room temperature about 24 h. Next, the mixture was neutralized by ice water and stirred for several minutes. Then, organic part was extracted using chloroform (10 ml × 3) and the organic phases were dried over anhydrous

Na_2SO_4 . Eventually, the organic solution was concentrated to obtain light brown crystal of 9-hydroxy-11-oxa[9]helicene (**9**) in excellent yield (Scheme 5.2).

Our next product 9-ethyleneglycoxy-11-oxa[9]helicene (**10**) was synthesized also from quinone (**7**) in good yield. First, quinone (**7**), ethylene glycol and *p*-toluene sulfonic acid (*p*-TSA) were charged in a round bottom flask with 1,2-dichloromethane (DCM). The reaction mixture was allowed to gentle stirring at room temperature about 5 h. Later, the mixture was concentrated under vacuum, and the crude product was purified by flash column chromatography on silica gel (ethyl acetate : n-hexane=8 : 2) to obtain pure light yellow 9-ethyleneglycoxy-11-oxa[9]helicene (**10**) compound in good yield (Scheme 5.3).



Scheme 5.3 Preparation and optical resolution of **10, 11, 12**

9-triethyleneglycoxy-11-oxa[9]helicene (**11**) and 9-hexaethyleneglycoxy-11-oxa[9]helicene (**12**) were also synthesized according to the reaction scheme 5.3 and the isolated product was in good yield. During the purification process, no other regioisomer was isolated from the reaction that means, the glycol molecules attract the ninth position regioselectively of the quinone ring.

The synthesized racemic products **9, 10, 11** and **12** were separated into its enantiomers on a preparative scale by HPLC on a Chiralflash IC column (3cmϕ×10cm) and chloroform/ethanol (95:5) as the mobile phase. Thus starting from 15±1 mg of r*ac*-**9,** a total of 12.2 mg of pure product were separated equivalent to a yield 81%. The earlier eluting fraction consisted of the enantiomer exhibiting an intense positive optical rotation (+) which was isolated in good yield (Scheme 5.2). Later eluting fraction gave negative optical rotation (-) in fair yield. In case of **10**, 25±1mg of *rac*-**10** was injected in the HPLC column and total of 21.1 mg of pure product were separated equivalent to a yield 84% (Table 5.1).

Table 5.1 Isolated yields of enantiomers of **9**, **10**, **11** and **12**

Entry	Compound	% yield [a]	R.T. / min[b]	mp. / ºC
1	(*P*)-(+)-**9**	47	7.49[c]	>300
2	(*M*)-(-)-**9**	34	9.76[c]	>300
3	(*P*)-(+)-**10**	47	8.54	137-140
4	(*M*)-(-)-**10**	45	11.62	135-138
5	(*P*)-(+)-**11**	49	9.34	86-88
6	(*M*)-(-)-**11**	35	10.50	86-88
7	(*P*)-(+)-**12**	35	11.11	58-62
8	(*M*)-(-)-**12**	34	11.91	59-62

[a] Yields were calculated after enantiomeric separation by chiral HPLC
[b]Retention time (RT) was obtained from analytical HPLC. Column: ChiralPak IA; Solvent ratio: n-hexane : $CHCl_3$ (50:50)
[c]HPLC. Column: ChiralPak IB; Solvent ratio: $CHCl_3$ (100%)

As like the previous one, the earlier fraction consisted of the enantiomer showing high positive optical rotation (+) and the isolated yield was good and the later one gave negative optical rotation (-) and yield was just like the earlier fraction. Compound **11** and **12** also enantiomerically separated according to the same method what we mention earlier and

obtained each enantiomer in a good yield and overall very good yields. The enantiomeric purity of **9, 10, 11** and **12** were determined by chiral HPLC using Chiralpak IA column and chloroform/n-hexane (50:50) as a mobile phase. The optical activities are reported in Table 5.2 as the specific optical rotation $[\alpha]_D$ (10^{-1} ° g^{-1} cm^2) values. The very high specific optical rotation values are one of the common features of helical molecules.

Table 5.2 Optical rotation and *% ee* of oxa[9]helicene derivatives

Entry	Compound [a]	Con. / (M) [d]	Specific OR $[\alpha]_D^{25}$	Molar OR $[\Phi]^e$	*% ee* [b]
1	(*P*)-(+)-**9**	1.20×10^{-4}	+1687	+8165	61[c]
2	(*M*)-(-)-**9**	1.21×10^{-4}	-1942	-9399	75[c]
3	(*P*)-(+)-**10**	1.06×10^{-4}	+1940	+10243	>99
4	(*M*)-(-)-**10**	1.06×10^{-4}	-2080	-10982	>99
5	(*P*)-(+)-**11**	1.06×10^{-4}	+1880	+11581	>99
6	(*M*)-(-)-**11**	1.07×10^{-4}	-1893	-11661	>99
7	(*P*)-(+)-**12**	8.08×10^{-5}	+1680	+12566	>99
8	(*M*)-(-)-**12**	8.95×10^{-5}	-1790	-13389	>99

[a] Separated by Recycling Preparative HPLC (Chiralflash IC column).
[b] % of *ee* was determined by analytical HPLC (Chiralpac IA column), mobile phase: n-hexane/$CHCl_3$=50/50.
[c] % of *ee* was determined by analytical HPLC (Chiralpac IB column), mobile phase: $CHCl_3$=100%.
[d] Solution prepared in MeCN for $[\alpha]_D^{25}$ measurement (D=589 nm).
[e] Molar Optical Rotation, $[\Phi]=10^{-2}\times[\alpha]_D\times M_w$

Unfortunately, neither of the any enantiomer of the compounds **9**, **10**, **11** and **12** afforded crystals suitable for the determination of their structure by X-ray diffraction. Nevertheless, we can assign the absolute configuration of each enantiomer based on circular dichroism (CD) spectra. The CD spectra of the dextrorotatory enantiomers (+)-**9, 10, 11, 12** starts with a positive band follower by a negative band. As expected, the spectra for levorotatory enantiomers (-)-**9**,**10, 11, 12** are the mirror image of the previous enantiomers (Figure 5.2). In the ^1B_b transition region, a strong positive cotton effect at 322 nm along with another strong positive cotton at 299 nm were observed for (**+**)-**9**, **10, 11, 12** enantiomers and at the same region an opposite cotton effect pattern were observed for (-)-**9**, **10, 11, 12** enantiomers

(**Table 3**). The CD shape of (+)-**9**, **10, 11, 12** correspond to the common fingerprint (+)-***P*** helicene derivatives. Thus, we could ascribe without any doubt (***P***) helicity to the dextrorotatory enantiomer and (***M***) helicity to the levorotatory enantiomer.

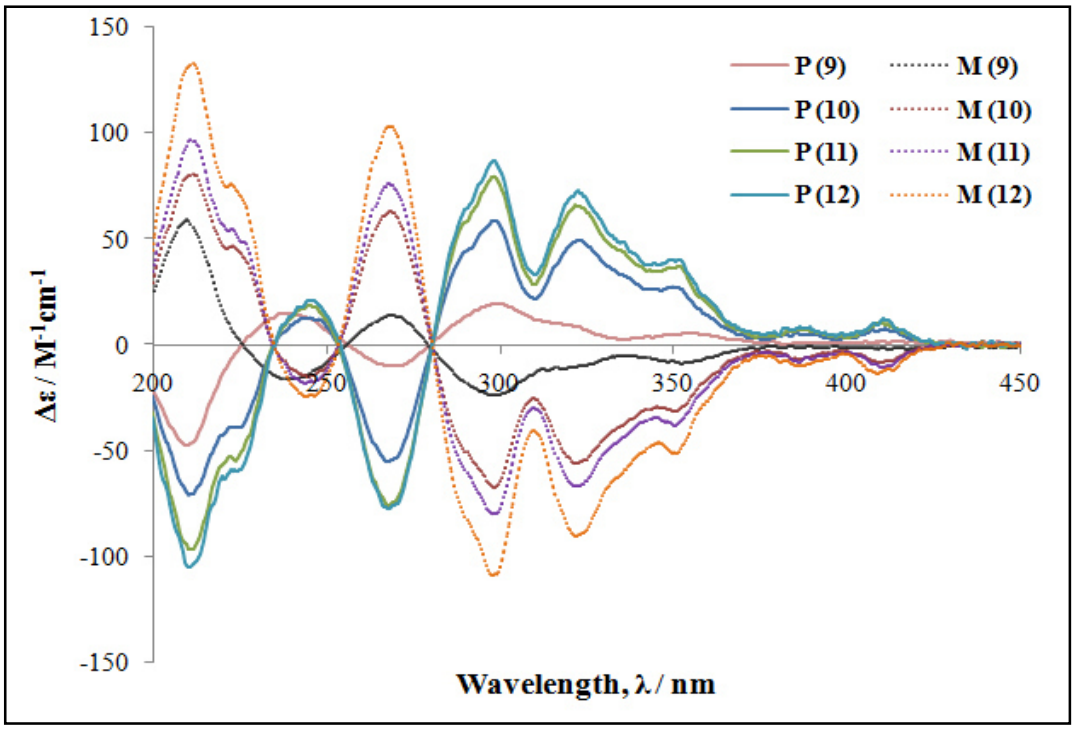


Figure 5.2 CD spectra of (***P***)-(+)-**9, 10, 11, 12** and (***M***)-(-)-**9, 10, 11, 12** in MeCN at 20°C

The optical properties of the amphiphilic oxa[9]helicene derivatives **9**,**10**, **11** and **12** were also investigated using UV-Vis absorption and photoluminescence (PL) at room temperature. The absorption bands were observed around 274, 309, 389, and 411 nm. The absorption peaks at the higher energy 274 nm and 309 nm ascribed to a π-π* transition, which is typical of fused aromatic compounds.

The peak located at 389nm and 411 nm would be ascribed to the n-π* transition of oxygen of ethylene oxide and hydroxyl group (Figure 5.4).[17]

Table 5.3 Summary of the Δε values of the ^1B_b bands for the both enantiomers of **9**, **10**, **11** and **12**

Entry	Compound	Δε / $M^{-1}cm^{-1}$	λ / nm
1	(*P*)-(+)-**9**	10	322
2	(*M*)-(-)-**9**	-10	322
3	(*P*)-(+)-**10**	50	321
4	(*M*)-(-)-**10**	-55	321
5	(*P*)-(+)-**11**	66	321
6	(*M*)-(-)-**11**	-66	322
7	(*P*)-(+)-**12**	73	322
8	(*M*)-(-)-**12**	-93	322

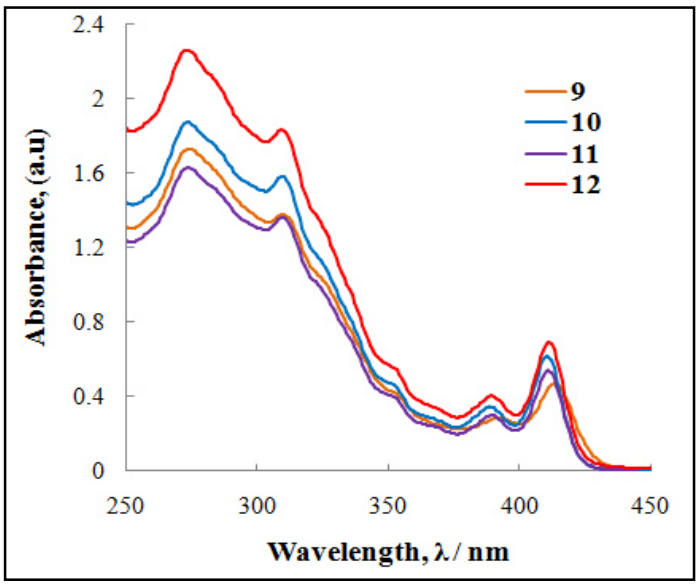


Figure 5.3 UV-Vis spectra of oxa[9]helicene derivatives at 4.05-5.34×10^{-5} M in $CHCl_3$ at 25°C

Moreover, the optical energy band gap $E_{opt.}$ were also calculated from the absorption band edge of the absorption spectra (Table 5.4). The fluorescence spectra indicated emission

maxima of every compound in the blue region around 420-424 nm with a shoulder peak around 440-442 nm indicating a Stokes shift about 9-11 nm (Figure 5.4, Table 5.4).

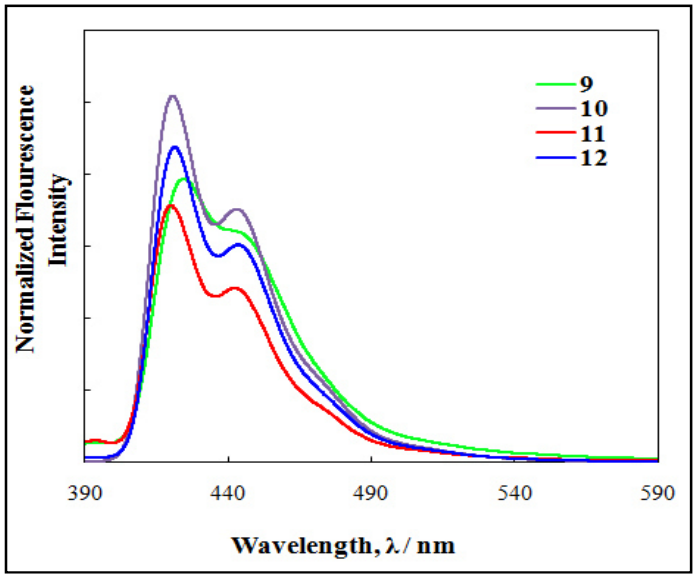


Figure 5.4 Photoluminescence spectra of oxa[9]helicene derivatives at 4.05-5.34×10^{-5} M in $CHCl_3$ at 25°C

Table 5.4 Optical properties of amphiphilic oxa[9]helicene derivatives

Compound	Absorption			Photoluminescence	
	λ_{max} (nm) [a]	λ_{onset} (nm)	E_{opt} (eV) [b]	λ_{ems} (nm) [c]	Stokes Shift / nm
9	274	433	2.86	424	11
10	273	428	2.89	421	11
11	274	430	2.88	420	9
12	273	426	2.91	421	10

[a] Absorption measured in a chloroform solution (4.05-5.34×10^{-5} M) at room temperature.
[b] Optical band gap (E_{opt}) were calculated by the following equation: $E_{opt} = 1240/\lambda_{onset}$.
[c] Emission spectra were measured in a chloroform solution (4.05-5.34×10^{-5} M) at room temperature.

5.3 EXPERIMENTAL PROCEDURE

5.3.1. Materials and Methods

All reagents were prepared using chemicals obtained from commercial sources and used without further purification. Most of the reactions were performed under aerobic or anaerobic conditions in oven-dried glassware with magnetic stirring. All reactions were monitored by analytical thin layer chromatography (TLC) using Merck pre-coated silica gel glass plates (0.25mm) and spot detected under either I_2 chamber or UV-lamp. The flash column chromatography was carried out over silica gel 60 (230–400 mesh), purchased from Kanto Chemical Co. Inc. Melting points were determined on a Yanagimoto melting point apparatus. Enantiomeric resolution was done by the recycling preparative HPLC (Japan Analytical Industry Co, Ltd., Model LC-908), equipped with Chiralflash IC column (Daicel Corporation, Japan) using $CHCl_3$ and ethanol mixture (95 : 5) as an eluent. Optically active oxa[9]helicene derivatives were analyzed by analytical HPLC (analytical HPLC system, apparatus, JASCO-880 PU and Hitachi L-4000 UV detector, Hitachi L-6000 pump) equipped with Chiralpak IA column (Daicel Corporation, Japan) using $CHCl_3$ and n-hexane mixture (50 : 50) as an eluent.

UV spectra were measured on a JASCO V-670, Spectrophotometer and sample were prepared as a solution with $CHCl_3$. FT-IR spectra were recorded on a JASCO FTIR spectrometer 4200; and samples were prepared as KBr (Sigma Aldrich, USA) plates. NMR spectra were recorded in $CDCl_3$ (Kanto Chemical Co. Inc.) at Varian NMR System 500 (Varian LTD) at 500 MHz for ^1H NMR and 125 MHz for ^{13}C NMR as well. The internal standard for NMR was 0.03% tetramethylsilane (TMS). Chemical shifts (δ) are given in ppm respect to TMS and coupling constants (*J*) are given in Hz. High-resolution mass spectra (HRMS) were acquired on a JMS-700AM (JEOL) spectrometer and JSM-777V (JEOL) spectrometer using EI (Electron Impact) and FAB (Fast Atom Bombardement) techniques. Photoluminescence property of the compounds was recorded through JASCO FP-6300 spectrophotometer. Enantiomerically pure compounds Circular Dichroism (CD) spectra were taken by JASCO J-725 spectropolatimeter, Light source: Xenon light (165-900 nm) in HPLC grade ACN solution (Kanto Chemical Co. Inc.). Specific optical rotation values were obtained by JASCO P-1010 polarimeter, Light source: Sodium light (D line at 589 nm).

5.3.2 General Experimental Procedure

5.3.2.1 Synthesis of 9-Hydroxy-11-oxa[9]helicene (9)

Quinone **7** (49 mg, 0.1 mmol) was added with anhydrous methanol (3 equiv.) with DCM in presence of *p*-TSA (3 equiv.) at room temperature for about 0.5 h. Later, the mixture was concentrated under vacuum and finally, the crude product was purified by column chromatography on silica gel (eluent: chloroform) to obtain 4-methoxy oxa[9]helicene (**8**) as light yellow crystal with excellent yield (97%, Scheme 5.2).

Later, the 4-Methoxy oxa[9]helicene **8** (210 mg, 0.43 mmol) was added with BBr_3 /CH_2Cl_2 (2.0 mL) at room temperature and gently stirred the mixture about 24 h. Next, ice water (30 ml) was poured drop wise into the reaction mixture and stirred several minutes. The organic part was extracted by $CHCl_3$ (3 × 10 mL) and dried over anhydrous Na_2SO_4. Finally, the organic solution was concentrated under vacuum and **9** was obtain as light brown solid with excellent yield (100%, Scheme 5.2).

5.3.2.1.1 *9-Methoxy-11-oxa[9]helicene (**8**):* Light yellow crystal, mp.:275-278ºC.^{1}H NMR ($CDCl_3$, 500 MHz , δ/ppm) : 4.31 (3H, s), 5.73 (1H, t, *J*=8.0 Hz), 5.79 (1H, t, *J*= 8.0 Hz), 6.27 (1H, d, *J*= 8.5 Hz), 6.31 (1H, d, *J*= 8.5 Hz), 6.74 (1H, d, *J*= 7.5 Hz), 6.75 (1H, d, *J*= 8.0 Hz), 7.28 (1H, d, *J*= 8.0 Hz), 7.30 (1H, d, *J*= 8.0 Hz), 7.36 (1H, d, *J*= 8.5 Hz), 7.37 (1H, d, *J*= 6.5 Hz), 7.53 (1H, d, *J*= 9.0 Hz), 7.55 (2H, d, *J*= 8.5 Hz), 7.58 (1H, d, *J*= 8.5 Hz), 7.68 (1H, s), 7.96 (1H, d, *J*= 8.0 Hz), 8.19 (1H, d, *J*= 8.5 Hz), 8.21 (1H, d, *J*= 8.0 Hz), 8.45 (1H, d, *J*= 8.5 Hz).^{13}C NMR ($CDCl_3$, 125 MHz , δ/ppm): 56.62, 91.94, 110.84, 114.74, 120.09, 121.75, 121.97, 122.35, 122.40, 124.16, 124.19, 124.22, 124.80, 124.90, 124.94, 125.36, 125.55, 125.58, 126.13, 126.43, 126.47, 126.49, 126.65, 126.71, 127.01, 127.32, 127.64, 127.72, 129.78, 129.81, 129.82, 130.01, 130.64, 153.95, 155.27, 156.36.

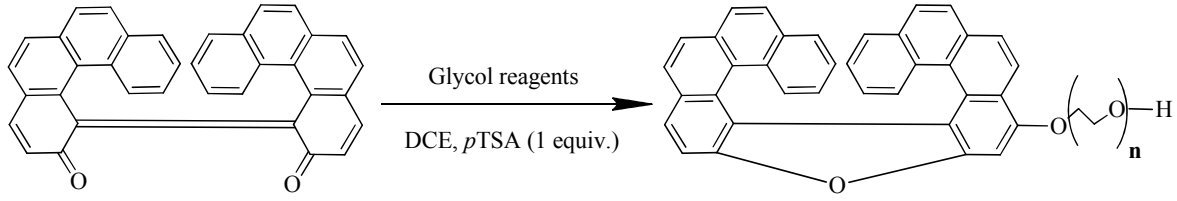
5.3.2.1.2 *9-Hydroxy-11-oxa[9]helicene (**9**):* Light brown crystal, mp.:>300ºC; IR(KBr) 3504, 3044, 3008, 1597, 1248, 1076, 832, 751 cm^{-1}; ^{1}H NMR ($CDCl_3$, 500 MHz) : δ = 5.30 (1H, s), 5.73 (1H, t, *J*=8.0 Hz), 5.80 (1H, t, *J*= 8.0 Hz), 5.90 (1H, s), 6.23 (1H, d, *J*= 8.5 Hz), 6.27 (1H, d, *J*= 8.5 Hz), 6.75 (1H, t, *J*= 8.0 Hz), 6.77 (1H, t, *J*= 8.0 Hz), 7.29 (1H, d, *J*= 8.0 Hz), 7.31 (1H, d, *J*= 8.0 Hz), 7.37 (1H, d, *J*= 9.0 Hz), 7.39 (1H, d, *J*= 9.5 Hz), 7.54-7.57 (2H, m), 7.59 (1H, d, *J*= 9.0 Hz), 7.68 (1H, s), 7.97 (1H, d, *J*= 8.0 Hz), 8.20 (2H, s), 8.36 (1H, d, *J*= 9.0 Hz). ^{13}C NMR ($CDCl_3$, 125 MHz, , δ/ppm) : δ = 96.07, 96.37, 110.84, 115.63,

119.56, 120.69, 121.57, 122.42, 122.45, 124.16, 124.23, 124.25, 124.74, 124.90, 125.06, 125.41, 125.54, 125.57, 125.91, 126.40, 126.44, 126.50, 126.70, 126.76, 127.03, 127.47, 127.55, 129.81, 130.07, 130.65, 151.93, 154.07, 154.61. HRMS (EI) calculated for $C_{36}H_{20}O_2$ $[M]^+$ 484.1463, found 484.1466.

5.3.2.2 General procedure for the synthesis of 9-glycoxy-11-oxa[9]helicene (10-14)

7 (49 mg, 0.1 mmol), ethylene glycol (5 equiv.) and *p*-TSA (1 equiv.) were charged in a round bottom flask with 1,2-dichloroethane. The reaction mixture was allowed to gentle stirring at room temperature for 4 h. Later, the mixture was concentrated under vacuum, and the crude product was purified by flash column chromatography on silica gel using ethyl acetate as a mobile phase to obtain **10** as a light yellow solid with good yield (74%).

Table 5.5 Synthesis of glycoxy oxa[9]helicene derivatives



7 **n= 1, 2, 3, 4, 6**

Entry[a]	**7 /** mg (mmol)	Glycol reagent / **n** (equiv.)	Time	Yield (%)[b]
1	49 (0.1)	Ethylene glycol **1** (5)	4	**10** (74)
2	98 (0.2)	Triethylene glycol **3** (4)	5	**11** (65)
3	49 (0.1)	Hexaethylene glycol **6** (5)	13	**12** (62)
4	98 (0.2)	Diethylene glycol **2** (5)	5	**13** (79)
5	98 (0.2)	Tetraethylene glycol **4** (5)	5	**14** (72)

[a] Reaction proceed at room temperature; [b] Isolated yield.

5.3.2.2.1. *9-Ethyleneglycoxy-11-oxa[9]helicene* ***(10):*** Yellowish crystal, mp.: 137-139ºC. IR(KBr) 3441, 3042, 2930, 1582, 1276, 1075, 831 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$, δ/ppm): δ = 8.47 (1H, d, *J*=8.5 Hz); 8.22 (1H, d, *J*=8.0 Hz); 8.20 (1H, d, *J*=8.5 Hz); 7.97 (1H, d, *J*=8.5 Hz); 7.71 (1H, s); 7.54-7.60 (4H, m); 7.37-7.39 (2H, m); 7.28 7.32 (2H, m); 6.76 (1H, t, *J*=8.0 Hz); 6.75 (1H, t, *J*=8.0 Hz); 6.30 (1H, d, *J*=8.0 Hz); 6.25 (1H, d, *J*=8.5 Hz); 5.80(1H, t, *J*=8.5 Hz); 5.73 (1H, t, *J*=8.0 Hz); 4.60-4.62 (2H, m); 4.30-4.33 (2H, m). ^{13}C NMR (125 MHz, $CDCl_3$, δ/ppm) : δ = 154.79, 154.73, 153.81, 130.39, 129.80, 129.58, 129.55, 127.41, 127.37, 127.19, 126.80, 126.51, 126.45, 126.25, 126.22, 126.19, 126.11, 125.31, 125.28, 125.17, 124.79, 124.69, 124.52, 123.99, 123.96, 122.19, 122.16, 121.60, 121.37, 119.64, 114.92, 110.63, 92.78, 70.50, 61.68. HRMS (FAB) calculated for $C_{38}H_{24}O_3$ $[M+H]^+$ 528.1725, found 528.1723.

5.3.2.2.2 *9-Triethyleneglycoxy-11-oxa[9]helicene* ***(11):*** Yellowish crystal, mp: 86-88ºC.IR(KBr) 3443, 3042, 2924, 1580, 1282, 1086, 831 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$, δ /ppm): δ = 8.48 (1H, d, *J*=8.5 Hz); 8.20 (1H, d, *J*=8.5 Hz); 8.19 (1H, d, *J*=8.5 Hz); 7.96(1H, d, *J*=8.5 Hz); 7.68 (1H, s); 7.52-7.58 (4H, m); 7.36-7.39 (2H, m); 7.27-7.31 (2H, m); 6.75 (1H, t, *J*=8.5 Hz); 6.74 (1H, t, *J*=8.0 Hz); 6.30 (1H, d, *J*=8.5 Hz); 6.25 (1H, d, *J*=8.0 Hz); 5.80(1H, t, *J*=8.0 Hz); 5.73 (1H, t, *J*=8.0 Hz); 4.62-4.64 (2H, m); 4.18-4.20 (2H, m); 3.90-3.92 (2H, m); 3.76-3.81 (4H, m); 3.67-3.69 (2H, m). ^{13} C NMR (125 MHz, $CDCl_3$, δ/ppm): δ = 155.31, 155.06, 154.02, 130.63, 130.02, 129.82, 129.81, 129.76, 127.68, 127.61, 127.35, 127.03, 126.73, 126.67, 126.48, 126.39, 126.26, 125.56, 125.53, 125.39, 124.92, 124.79, 124.22, 124.19, 124.17, 122.44, 122.37, 122.04, 121.67, 120.25, 115.01, 110.86, 93.04, 72.80, 71.40, 70.81, 70.13, 69.01, 62.13. HRMS (EI) calculated for $C_{42}H_{32}O_5$ $[M]^+$ 616.2249, found 616.2240.

5.3.2.2.3 *9-Hexaethyleneglycoxy-11-oxa[9]helicene* ***(12):*** Yellowish crystal, mp: 56-58ºC. IR (KBr) 3432, 3046, 2924, 1581, 1278, 1086, 836 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$, δ/ppm): δ = 8.47 (1H, d, *J*=8.5 Hz); 8.20 (1H, d, *J*=8.5 Hz); 8.19 (1H, d, *J*=8.5 Hz); 7.96 (1H, d, *J*=8.0 Hz); 7.70 (1H, s); 7.52-7.57 (4H, m); 7.36-7.39 (2H, m); 7.27-7.31 (2H, m); 6.76 (1H, t, *J*=8.0 Hz); 6.75 (1H, t, *J*=8.0 Hz); 6.30 (1H, d, *J*=8.5 Hz); 6.25 (1H, d, *J*=8.0 Hz); 5.80(1H, t, *J*=8.0 Hz); 5.73 (1H, t, *J*=8.0 Hz); 4.64 (2H, m); 4.40 (2H, m); 4.38 (2H, m); 4.18 (2H, m); 3.56-3.79 (12H, m). ^{13} C NMR (125 MHz, $CDCl_3$, δ /ppm) : δ = 155.42, 155.12, 154.01, 130.63, 130.02, 129.82, 129.76, 127.69, 127.63, 127.32, 127.01, 126.71, 126.66, 126.48, 126.38, 126.21, 125.54, 125.36, 124.90, 124.87, 124.78, 124.22, 124.18, 122.45, 122.35,

122.07, 121.69, 120.36, 114.92, 110.86, 93.01, 92.97, 72.62, 71.36, 71.28, 70.99, 70.92, 70.86, 70.83, 70.79, 70.77, 70.71, 70.63, 70.32, 70.12, 69.06, 68.42, 61.93. HRMS (EI) calculated for $C_{48}H_{44}O_8$ $[M]^+$ 748.3036, found 748.3030.

5.3.2.2.4 *9-Diethyleneglycoxy-11-oxa[9]helicene* ***(13):*** Yellowish crystal, mp.: 224-228^{o}C. IR (KBr) 3421, 3042, 2869, 1578, 1284, 1087, 830cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$, ,δ/ppm): 8.47 (1H, d, *J*=8.5 Hz); 8.20 (1H, d, *J*=8.5 Hz); 8.19 (1H, d, *J*=8.5 Hz); 7.97 (1H, d, *J*=8.5 Hz); 7.69 (1H, s); 7.52-7.58 (4H, m); 7.35-7.38 (2H, m); 7.25-7.31 (2H, m); 6.77 (1H, t, *J*=8.5 Hz); 6.74 (1H, t, *J*=7.5 Hz); 6.30 (1H, d, *J*=8.5 Hz); 6.25 (1H, d, *J*=8.0 Hz); 5.81(1H, t, *J*=7.5 Hz); 5.74 (1H, t, *J*=7.5 Hz); 4.62-4.65 (2H, m); 4.19 (2H, t, *J*=4.5 Hz); 3.84-3.86 (4H, m);^{13}C NMR (125 MHz, $CDCl_3$, δ/ppm): 155.27, 155.09, 154.04, 130.65, 130.04, 129.83, 129.82, 129.78, 127.68, 127.62, 127.37, 127.04, 126.74, 126.67, 126.49, 126.48, 126.40, 126.28, 125.55, 125.52, 125.42, 125.40, 125.02, 124.92, 124.79, 124.24, 124.21, 124.18, 122.45, 122.37, 122.03, 121.66, 120.13, 115.08, 110.85, 92.02, 72.98, 70.04, 69.02, 62.18; HRMS (EI) calculated for $C_{40}H_{28}O_4$ $[M]^+$ 572.1987, found 572.1977.

5.3.2.2.5 *9-Tetraethyleneglycoxy-11-oxa[9]helicene* ***(14):*** Yellowish crystal, mp.: 148-151^{o}C. FT-IR (KBr): 3442.31cm^{-1} (-OH str.), 3042.16cm^{-1} (-CH str. in benzene ring), 1638cm^{-1} (-CO str.); ^{1}H NMR (500 MHz, $CDCl_3$, δ/ppm): δ = 8.48 (1H, d, *J*=8.5 Hz); 8.21 (1H, d, *J*=8.5 Hz); 8.19 (1H, d, *J*=10.0 Hz); 7.96(1H, d, *J*=8.0 Hz); 7.60 (1H, s); 7.58-7.52 (4H, m); 7.39-7.36 (2H, m); 7.31-7.27 (2H, m); 6.75 (1H, t, *J*=8.0 Hz); 6.74 (1H, t, *J*=7.5 Hz); 6.30 (1H, d, *J*=8.5 Hz); 6.25 (1H, d, *J*=8.0 Hz); 5.80(1H, t, *J*=7.5 Hz); 5.73 (1H, t, *J*=7.0 Hz); 4.64 (2H, m); 4.19 (2H, m); 3.92-3.91 (2H, m); 3.80-3.79 (2H, m); 3.73-3.69 (6H, m), 3.60 (2H, m).^{13} C NMR (125 MHz, $CDCl_3$, δ /ppm) : 155.36, 155.09, 154.02, 130.63, 130.02, 129.82, 129.77, 127.69, 127.63, 127.34, 127.02, 126.73, 126.66, 126.48, 126.39, 126.23, 125.56, 125.54, 125.38, 124.90, 124.89, 124.78, 124.23, 124.18, 124.16, 122.44, 122.36, 122.06, 121.69, 120.30, 114.98, 110.86, 93.02, 72.75, 71.34, 70.96, 70.94, 70.59, 70.13, 69.04, 62.00. HRMS (FAB) calculated for $C_{44}H_{36}O_6$ $[M+H]^+$ 660.2511, found 660.2538.

5.4 CONCLUSION

In this chapter, I have successfully synthesized and characterized a new class of amphiphilic oxa[9]helicene derivatives in racemic form with excellent to very good yield. The enantiomeric resolution of the racemic **9**, **10**, **11** and **12** were successfully achieved and obtained corresponding enantiomers in high optical purity. The absolute configuration of each isomer was confirmed by the CD spectra. These helical compounds **9**, **10**, **11**, **12**, **13** and **14** could be applied on thin film,[17,18] ligand in asymmetric synthesis, optoelectronics and so on. This type of research work is currently going on with the collaboration of another research group.

5.5 REFERENCES

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CHAPTER 6

Optical resolution of helical quinone derivatives through diastereomeric process

Synopsis

Synthesis of optical pure quinone derivative through diastereomeric process is achieved. The diastereomer was separated by preparative HPLC and separation was confirmed by ^{1}H NMR spectroscopy. The absolute configurations of the diastereomers as well as the optically pure quinone derivative were confirmed by circular dichroism (CD) spectroscopy. Analytical HPLC revealed that (*P*) and (*M*)-**3a**, **3c** isomers have high optical purity. Other optical properties (e.g. UV, Specific Optical Rotation) of the compound were also examined as well.

CHAPTER 6

6.1 INTRODUCTION

Helicenes and helicenes like molecules are attracting more and more attention due to their unique screw-shaped and π-conjugated aromatic system consisting *ortho*-spherical either aromatic or hetero aromatic rings. After increasing the number of *ortho*-annulated rings (normally, $n \geq 5$), these molecules adopt a helical conformation to avoid overlapping of the terminal aromatic nuclei resulting in left- and right- handed chiral helical structures of ***P*** and ***M*** configuration respectively.[1,2]

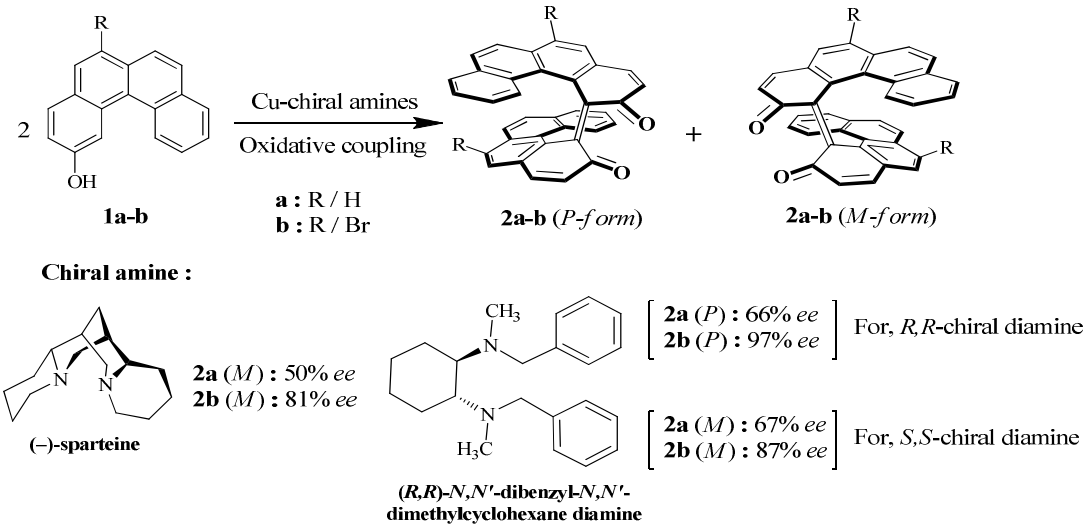
The extraordinary high chiral properties of helicene and helicene like molecules enhance the development of synthetic approaches to optically pure helicene molecules for further applications in more advanced material sciences including organic light emitting diode (OLED) materials,[3] organic field-effect transistors (OFET) [4] and so on.

Optical resolution of helicene molecules is quite rare except few literatures are available on online. Although we have already shown the simplest way of the synthesis of helical quinone derivatives from commercially available simple molecules with excellent to good yield, [5] we have also shown the halogenation reactions with quinone derivatives to form halo substituted oxa[9]helicene derivatives.[6] In all cases the products were in 1:1 ratio of ***P*** and ***M*** isomers.

In 2014, our research group had shown asymmetric synthesis of quinone derivatives from 2-hydroxybenzo[c]phenanthrenes using chiral amine-copper complexes (Scheme 6.1). The results were not good for non-substituted quinone (66% *ee* for ***P*** and 67% *ee* for ***M*** isomers) and in case of bromo-substituted quinone the results is much better (97% *ee* for ***P*** and 87% *ee* for ***M*** isomers). [7] Bis-oxazolin ligand also used for the asymmetric synthesis of quinone derivatives but results was not quite satisfactory at all.

Although asymmetric synthesis is the first growing method for the synthesis of optically pure organic molecules but this method is still not suitable for helical molecules.

This chapter shows the effective method of high optical resolution of helical quinone molecule through diastereomeric separation technique using chiral reagent. Diastereomeric resolution is the most convenient and easiest method for the separation of enantiomers

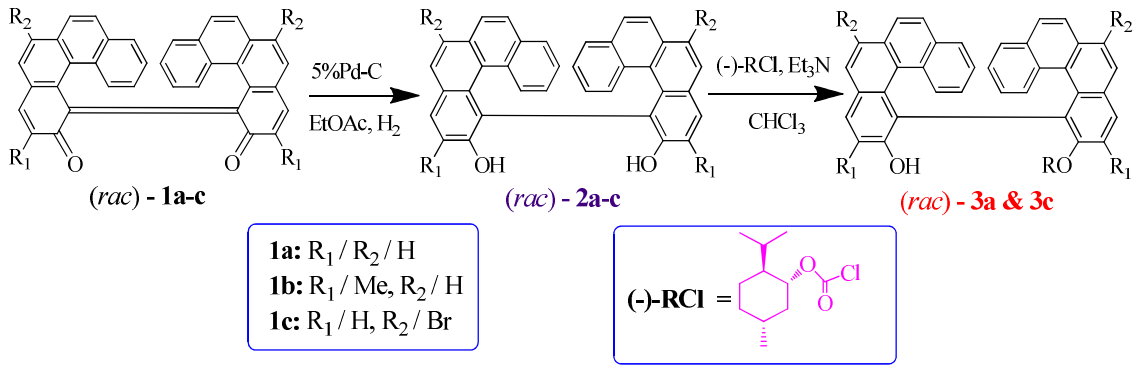


Scheme 6.1 Asymmetric synthesis of quinone derivatives using chiral diamines [7]

6.2 RESULTS AND DISCUSSIONS

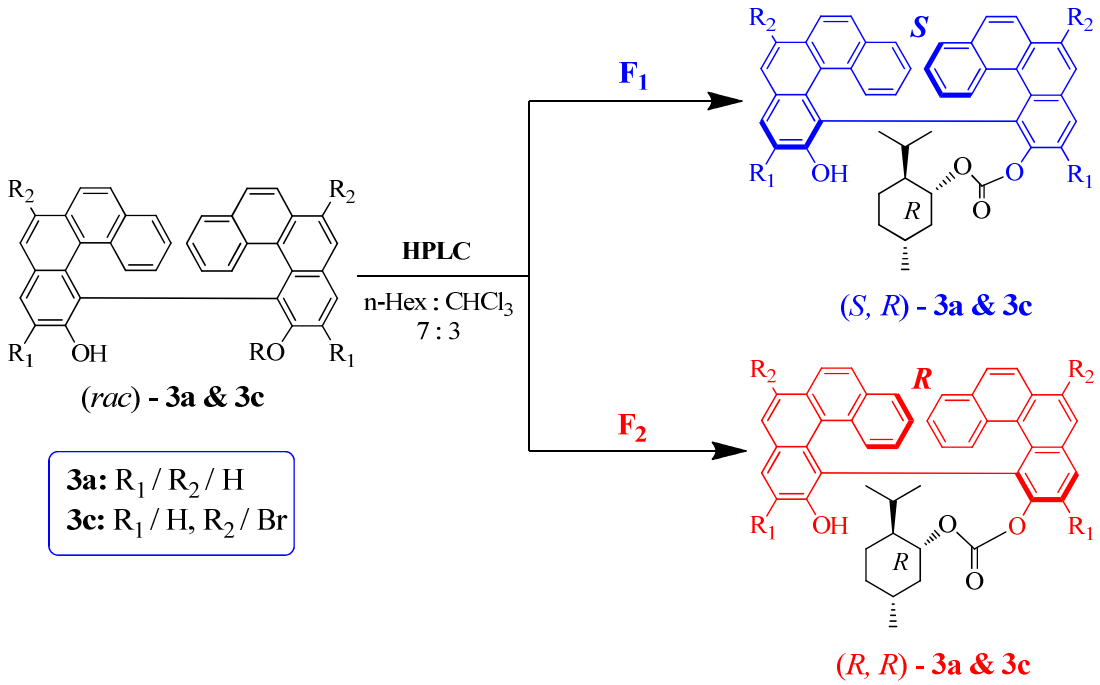
Chapter 3 shows the easy synthetic way of the BIPOL ([1,1'-bibenzo[c]phenanthrene]-2,2'-diol) type derivatives with excellent yield (see chapter 3). Having obtained the chiral BIPOL (*S/R*)-**2a-c** from quinone derivatives (*P*/*M*)-**1a-c** next we studied their resolution. To perform this resolution we investigated the utility of (*1R*)-(-)-menthyl chloroformate as a chiral resolving agent, which was used to convert related BIPOL's into their corresponding diastereomer (*S,R*)-**3a-c**, and (*R,R*)-**3a-c** respectively. From ^{1}H NMR spectra it was clear that incase of **2b**, the diastereomer **3b** not formed. The reason might be due to bulky methyl group at -R_1 position; which imposed steric hindrance to the (*1R*)-(-)-menthyl chloroformate to come closer to **2b** during reaction. ^{1}H NMR spectra also revealed that the product was not other than starting materials **2b**.

However, treatment of racemic BIPOL (*S/R*)-**2a** and **2c** with (*1R*)-(-)-menthyl chloroformate, in the presence of triethylamine (Et_3N) and $CHCl_3$ at room temperature for 4 h, led to a 1:1 mixture (confirmed by ^{1}H NMR) of two diastereomer (*S,R*)-**3a**, **3c** and (*R,R*)-**3a**, **3c** in an excellent combined yield (99%); scheme 6.2.



Scheme 6.2 Synthesis of diastereomers using chiral reagent

The first attempt was to separate the diastereomers of **3a** and **3c** use of chromatographic column over different silica gel (gravity column, flash column). Different solvent mixtures were also tried, but none of them proved suitable. Later, another attempt to separate these diastereomers by fractional crystallization were not successful. However, the diastereomers were satisfactorily separated by preparative recycling HPLC. The diastereomeric mixture (95±5 mg) of **3a** and (60±5 mg) of **3c** were eluted at room temperature on a Cica-MERCK Si60 HPLC (φ 20 mm × 250 mm) column with n-hexane / $CHCl_3$ (7:3 v/v); flow rate 3.8 ml/min; temperature 293K; detection: UV, λ = 254 nm. TLC analyzed the eluted fractions. The TLC shows only single spot for each fraction. The earlier eluting fraction (F1) consisted of the (*S,R*)-**3a**, **3c** which were obtained 34% (33 mg) and 33% (21 mg) yields respectively and the later eluting fraction gave the second diastereomer (*R,R*)-**3a, 3c** in 44% (42 mg) and 37% (23 mg) yields respectively (Scheme 6.3, Table 6.1).



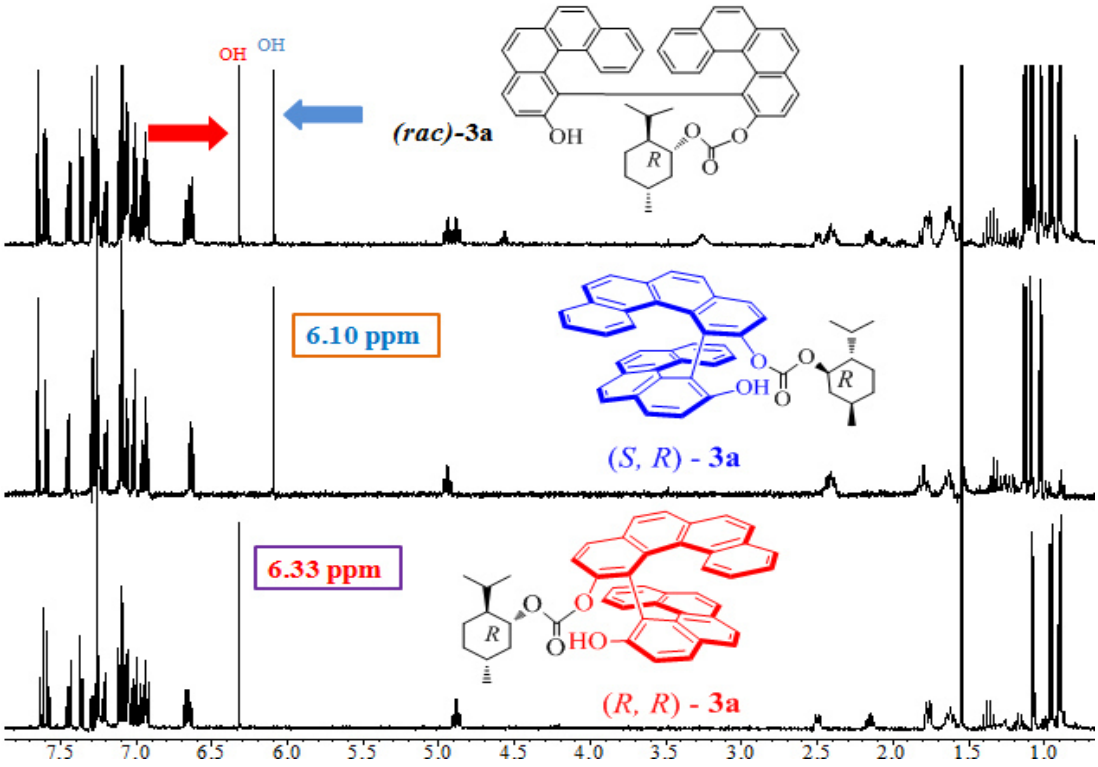
Scheme 6.3 Diastereomeric separation through preparative HPLC

Table 6.1 % of yield of diastereomers after successful separation using HPLC

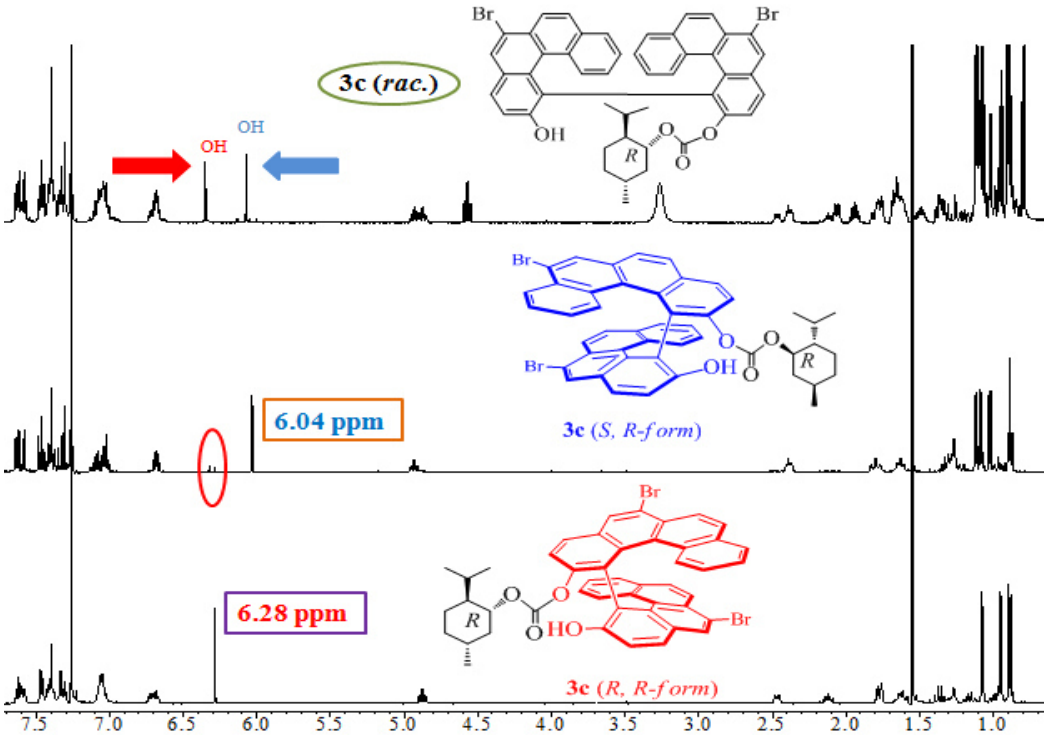
Entry	Compound[a]	%Yield[b]	mp. / ºC
1	(*S, R*)-**3a**	34	254-256
2	(*R, R*)-**3a**	44	239-241
3	(*S, R*)-**3c**	33	169-171
4	(*R, R*)-**3c**	37	166-170

[a] Separated by Recycling Preparative HPLC (Cica-MERCK Si60 column: φ 20 mm ×250 mm)
[b] Yields were calculated after separation

The purities of **3a, 3c** diastereomers were determined by ^{1}H NMR spectroscopy. In the ^{1}H NMR spectra, the -OH proton gave characteristic signals at 6.10 ppm (s) for (*S,R*)-**3a** and 6.33ppm (s) for (*R,R*)-**3a** respectively. The comparative ^{1}H NMR of **3a** and **3c** show that (Fig 6.1) the preparative HPLC effectively separated the diastereomers.



(a)

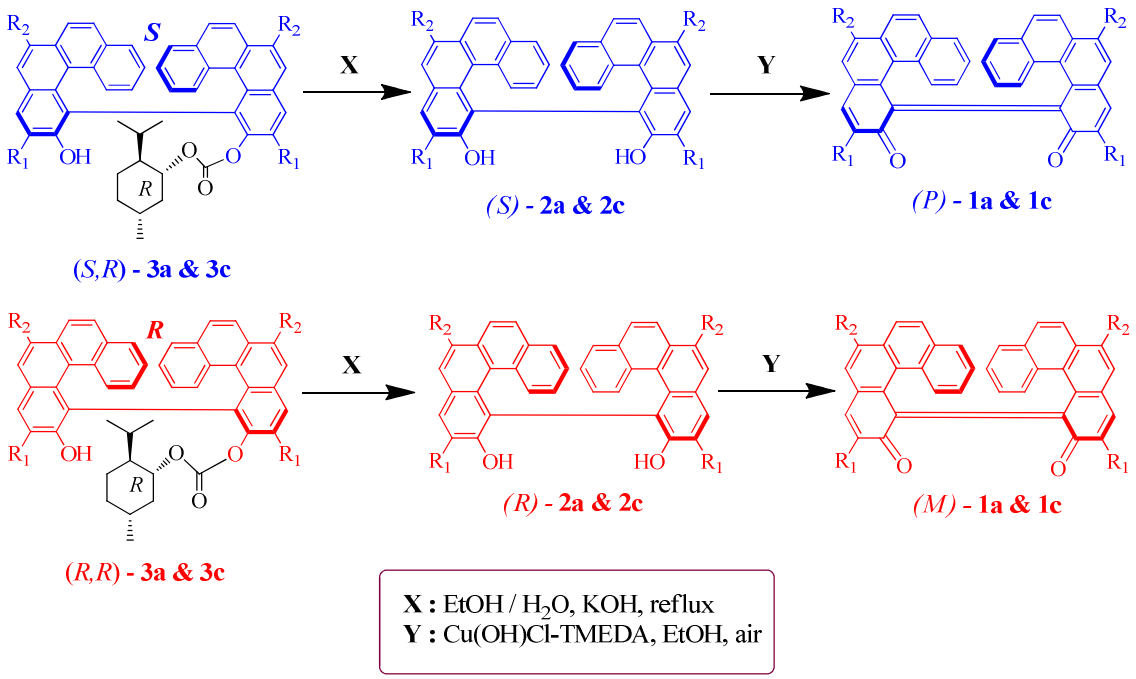


(b)

Figure 6.1 Comparative ^{1}H NMR spectra of diastereomers (a) **3a** and (b) **3c**

However, in the case of **3c** (Fig 6.1, b) the first diastereomer (*S, R*)-**3c** contains a little bit of (*R, R*)-**3c** (red circle). The specific optical rotation values for (*S,R*)-**3a, 3c** and (*R,R*)-**3a, 3c** were found very high which is one of the characteristic feature of helical structures, while the sign of the optical rotation allows reliable assignment of the helical configuration (Table 6.2).

Afterwards, the de-protection of the diastereomers (*S,R*)-**3a, 3c** and (*R,R*)-**3a, 3c** was carried out smoothly at reflux in 1:4 (v/v) aqueous EtOH with more than 4 equiv of KOH gave the corresponding BIPOL (*S*)-(+)-**2a, 2c** and (*R*)-(-)-**2a, 2c** respectively, in excellent yields. The BIPOL's are subjected for the next oxidation reaction with CuCl(OH)-TMEDA and we obtained highly optically active quinone derivatives (*P*)-(+)-**1a, 1c** and (*M*)-(-)-**1a, 1c** fair to moderate yields (Scheme 6.4).



Scheme 6.4 Synthesis of optically pure quinone

Table 6.2 Specific Optical Rotation values of **3a**, **3c**, **2a** and **2c** isomers

Entry	Compound	Con. / (M) [a]	Specific OR $[\alpha]_D^{25}$	Molar OR $[\Phi]^b$
1	(*S, R*)-**3a**	9.63×10^{-5}	+1130	+7549

2	(*R, R*)-**3a**	9.63×10^{-5}	-1022	-6827
3	(*S, R*)-**3c**	6.24×10^{-6}	+560	+4629
4	(*R, R*)-**3c**	6.25×10^{-6}	-645	-5332
5	(*S*)-**2a**	1.23×10^{-4}	+1380	+6707
6	(*R*)-**2a**	1.23×10^{-4}	-1360	-6610
7	(*S*)-**2c**	8.10×10^{-5}	+953	+6119
8	(*R*)-**2c**	8.10×10^{-5}	-1059	-6799

[a] Solution prepared in MeCN for $[\alpha]_D^{25}$ measurement (D=589 nm)
[b] Molar Optical Rotation, $[\Phi]=10^{-2}\times[\alpha]_D\times M_w$

The specific optical rotation values for (*P*)-(+)-**1a, 1c** and (*M*)-(-)-**1a, 1c** at 25ºC in MeCN for **1a** and in $CHCl_3$ for **1c** were measured respectively (Table 6.3).

The UV-absorption bands were observed around 274, 375 and 395 nm (Fig.6.2). The absorption peaks at the higher energy 274 nm and 375 nm ascribed to a π-π* transition, which is typical of fused aromatic compounds. The absorption at 395 nm would be attributed to an n-π* transition. The chiroptical properties of 1,1'-Bibenzo[c]phenanthryliden-2,2'-dione **1a** in the form of CD spectrum along with the diastereomer-**3a** and BIPOL-**2a** were also investigated (Fig. 6.3).

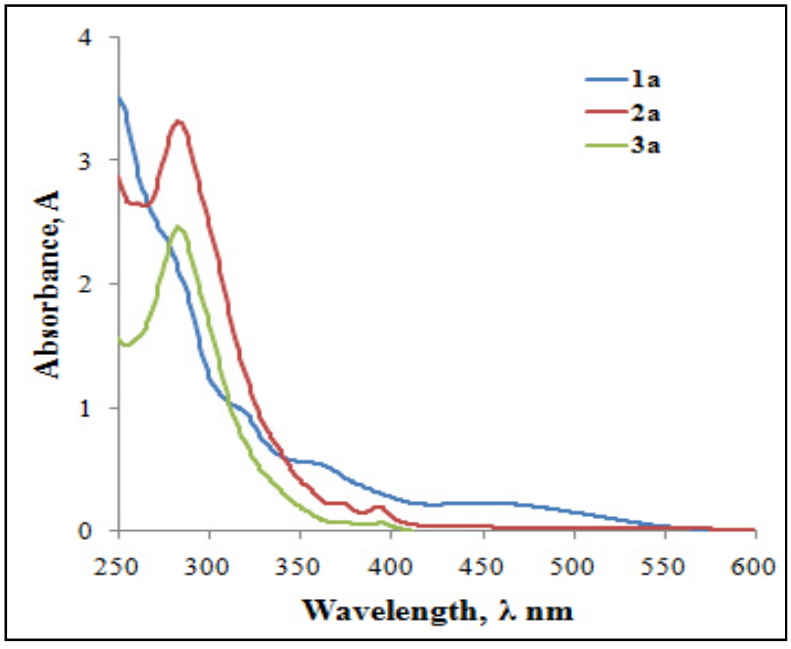
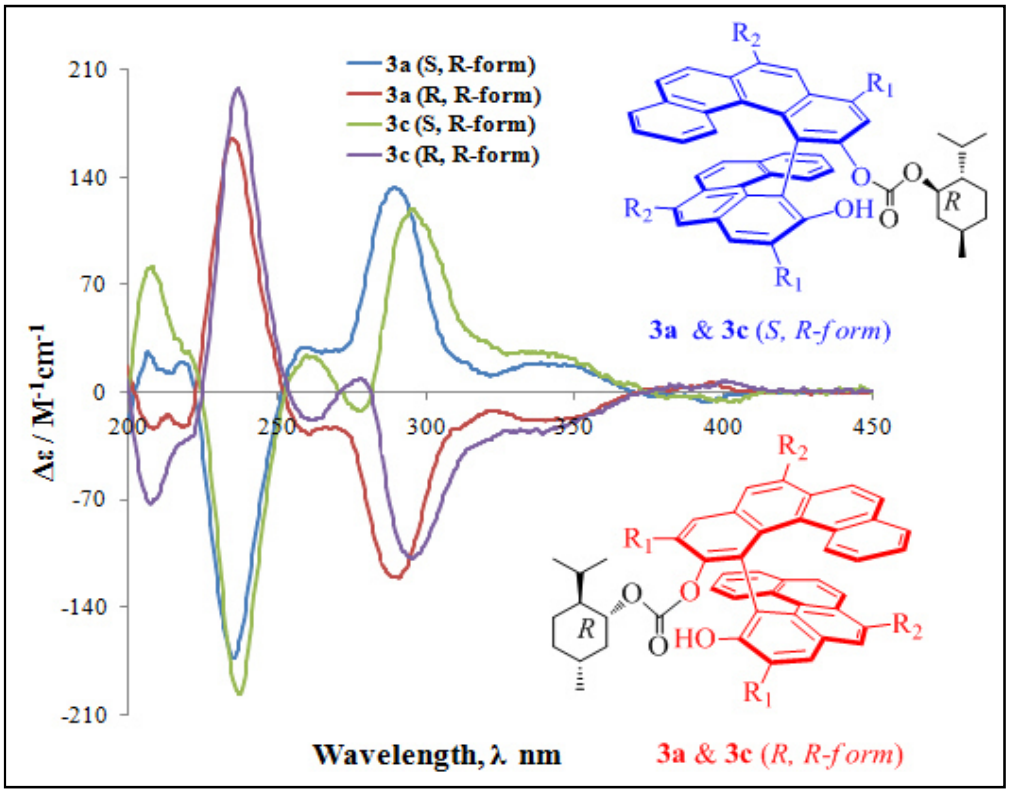
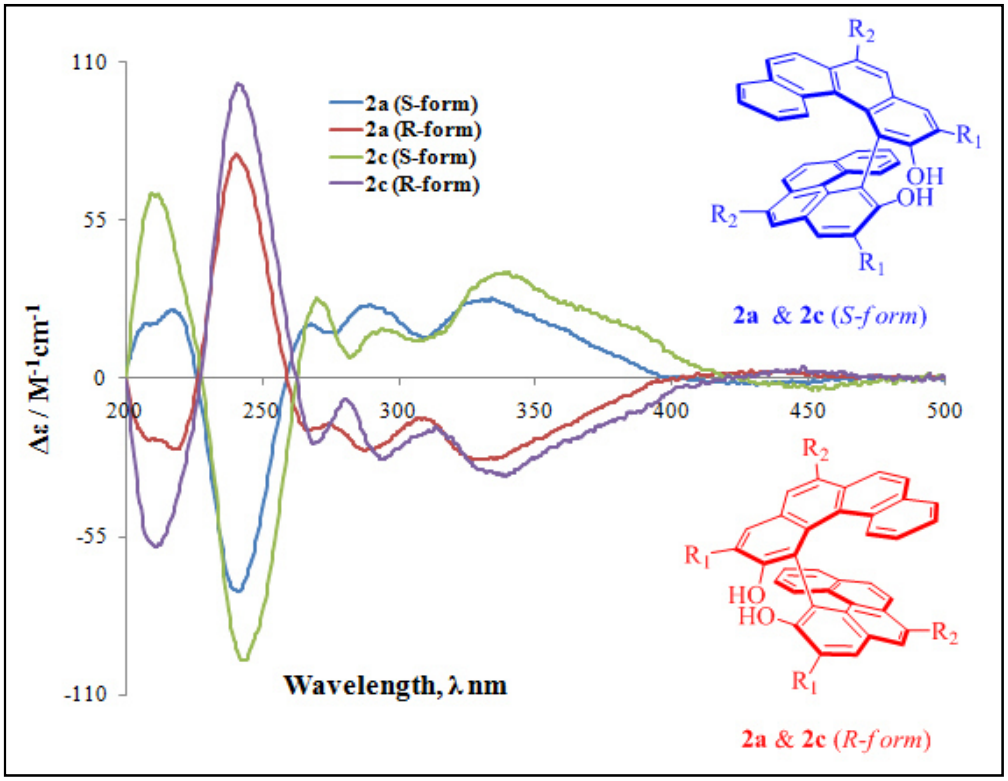


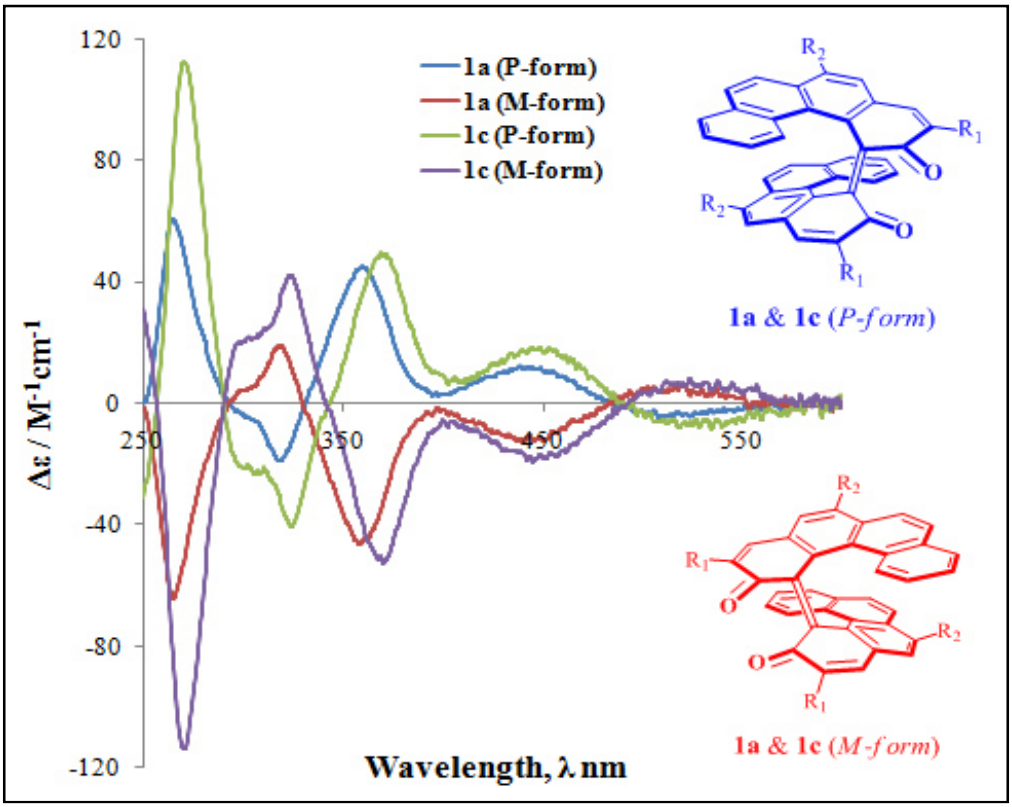
Figure 6.2 UV-vis spectra of **1a**, **2a** and **3a** at $4.0\text{-}5.2\times10^{-5}$ M in $CHCl_3$ at 25°C


3a (S, R-form)
3a (R, R-form)
3c (S, R-form)
3c (R, R-form)
Δε / M-1cm-1
Wavelength, λ nm
3a & 3c (S, R-form)
3a & 3c (R, R-form)

(a)


2a (S-form)
2a (R-form)
2c (S-form)
2c (R-form)
Δε / M-1cm-1
Wavelength, λ nm
2a & 2c (S-form)
2a & 2c (R-form)

(b)



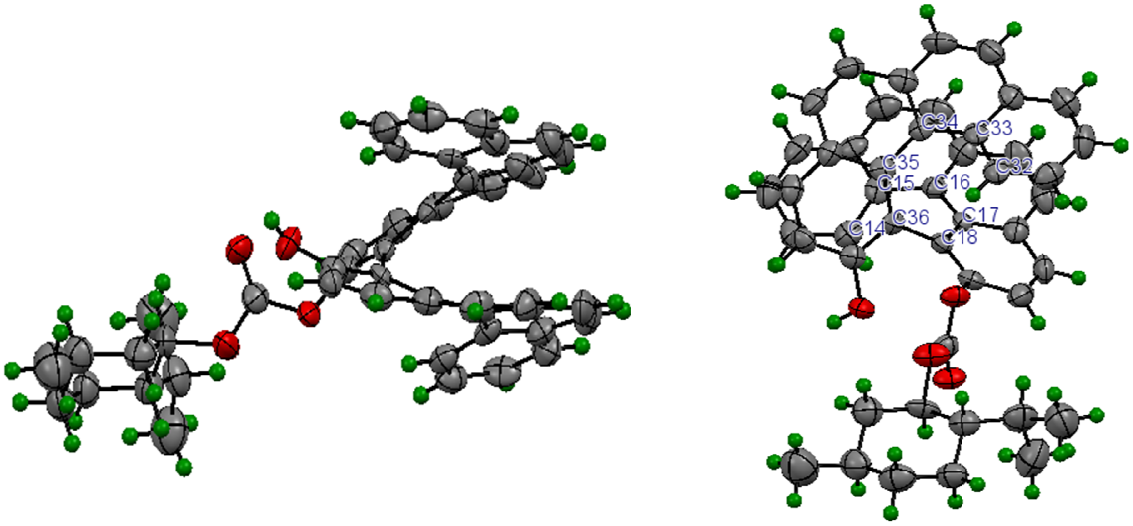
(c)

Figure 6.3 Circular Dichroism (CD) spectra of (a) diastereomers; (b) BIPOL's and (c) quinones

We can assign the absolute configuration of each enantiomer based on circular dichroism (CD) spectra. CD spectra indicated that complete resolution had occurred. The CD spectra of dextrorotatory enantiomer (*P*)-(+)-**1a** exhibited a distinct positive maximum around 285 nm and a negative maximum around 215 nm. The levorotatory enantiomer (*M*)-(-)-**1a** also shows the exact maximum values but in opposite direction.

We have also successfully made good crystals of (*R, R*)-**3a** using cyclohexane and $CHCl_3$ (7:3 v/v) solvent mixture. Finally, the absolute configuration of the crystal was confirmed by X-ray crystallographic data analysis. The negative sign of internal dihedral angles suggested that the crystal structure is for '*R*' conformer. The torsion angle between the two benzo[c]phenanthrene moieties of (*R, R*)-**3a** is little bit large (C17-C18-C36-C34 = - 41.64) compare to BIPOL (Chapter 3) crystal structure. That means the (*1R*)-(-)-menthyl formate unit imposed some sort of steric repulsion onto the benzo[c]phenanthrene moieties.

Table 6.3 Selective dihedral angle (°) of (*R, R*)-**3a**



(a) Side view **(b) Top view**

C-C bonds	Dihedral angle (°)
C14–C15–C16–C17	-20.64
C15–C16–C17–C18	-31.74
C16–C17–C18–C36	-15.23
C17–C18–C36–C35	**-41.64**
C18–C36–C35–C34	-14.15
C36–C35–C34–C33	-30.38
C35–C34–C33–C32	-20.58

Table 6.4 Specific Optical Rotation values of **3a**, **3c**, **2a** and **2c** isomers

Entry	Compound[a]	Con. / (M) [a]	Specific OR $[\alpha]_D^{25}$	Molar OR $[\Phi]$[b]
1	(*S, R*)-**3a**	9.63×10^{-5}	+1130	+7549
2	(*R, R*)-**3a**	9.63×10^{-5}	-1022	-6827
3	(*S, R*)-**3c**	6.24×10^{-6}	+560	+4629

4	(*R, R*)-**3c**	6.25×10^{-6}	-645	-5332
5	(*S*)-**2a**	1.23×10^{-4}	+1380	+6707
6	(*R*)-**2a**	1.23×10^{-4}	-1360	-6610
7	(*S*)-**2c**	8.10×10^{-5}	+953	+6119
8	(*R*)-**2c**	8.10×10^{-5}	-1059	-6799

[a] Solution prepared in MeCN for $[\alpha]_D^{25}$ measurement (D=589 nm)
[b] Molar Optical Rotation, $[\Phi]=10^{-2}\times[\alpha]_D\times M_w$

Thus, the absolute configuration of (-)- and (+)-helical quinone **1a, 1c** must be ***M*** (left-handed helix) and *P* (right-handed helix), respectively. Analytical HPLC confirmed the high *% ee* for every enantiomers (Table 6.4).

Table 6.5 Specific optical rotation and *% ee* values of **1a** and **1c**

Entry	Compound	Con. / (M) [a]	Specific OR $[\alpha]_D^{25}$	Molar OR $[\Phi]^c$	*% ee*	mp. / ºC
1	(*P*)-**1a**	1.05×10^{-4}	+1530[a]	+7406	100[d]	222-225
2	(*M*)-**1a**	7.44×10^{-5}	-1460[a]	-7066	>99[d]	205-208
3	(*P*)-**1c**	3.90×10^{-3}	+2070[b]	+13248	86[e]	258-262
4	(*M*)-**1c**	3.44×10^{-3}	-3213[b]	-20563	100[e]	249-251

[a] Solution prepared in MeCN for $[\alpha]_D^{25}$ measurement (D=589 nm)
[b] Solution prepared in $CHCl_3$ for $[\alpha]_D^{25}$ measurement (D=589 nm)
[c] Molar Optical Rotation, $[\Phi]=10^{-2}\times[\alpha]_D\times M_w$
[d] % of *ee* was determined by analytical HPLC (Chiralpac IA column), mobile phase: MTBE
[c] % of *ee* was determined by analytical HPLC (Chiralpac IA column), mobile phase: n-Hexane/EtOAc: 6/4 (v/v)

6.3 EXPERIMENTAL PROCEDURE

6.3.1 Materials and Methods

All reagents were prepared using chemicals obtained from commercial sources and used without further purification. Most of the reactions were performed under aerobic or anaerobic conditions in oven-dried glassware with magnetic stirring. All reactions were monitored by analytical thin layer chromatography (TLC) using Merck pre-coated silica gel glass plates

(0.25mm) and spot detected under either I_2 chamber or UV-lamp. The flash column chromatography was carried out over silica gel 60 (230–400 mesh), purchased from Kanto Chemical Co. Inc. Melting points were determined on a Yanagimoto melting point apparatus. Enantiomeric resolution was done by the recycling preparative HPLC (Japan Analytical Industry Co, Ltd., Model LC-908), equipped with Chiralflash IC column (Daicel Corporation, Japan) using $CHCl_3$ and ethanol mixture (95 : 5) as an eluent. Optically active oxa[9]helicene derivatives were analyzed by analytical HPLC (analytical HPLC system, apparatus, JASCO-880 PU and Hitachi L-4000 UV detector, Hitachi L-6000 pump) equipped with Chiralpak IA column (Daicel Corporation, Japan) using $CHCl_3$ and n-hexane mixture (50 : 50) as an eluent.

UV spectra were measured on a JASCO V-670, Spectrophotometer and sample were prepared as a solution with $CHCl_3$. FT-IR spectra were recorded on a JASCO FTIR spectrometer 4200; and samples were prepared as KBr (Sigma Aldrich, USA) plates. NMR spectra were recorded in $CDCl_3$ (Kanto Chemical Co. Inc.) at Varian NMR System 500 (Varian LTD) at 500 MHz for ^1H NMR and 125 MHz for ^{13}C NMR as well. The internal standard for NMR was 0.03% tetramethylsilane (TMS). Chemical shifts (δ) are given in ppm respect to TMS and coupling constants (*J*) are given in Hz. High-resolution mass spectra (HRMS) were acquired on a JMS-700AM (JEOL) spectrometer using FAB (Fast Atom Bombardment) technique. Enantiomerically pure compounds Circular Dichroism (CD) spectra were taken by JASCO J-725 spectropolatimeter, Light source: Xenon light (165-900 nm) in HPLC grade ACN solution (Kanto Chemical Co. Inc.). Specific optical rotation values were obtained by JASCO P-1010 polarimeter, Light source: Sodium light (D line at 589 nm).

X-ray diffraction of the single crystals were recorded using CrystalClear (Rigaku/MSC, 2006), CrystalClear, SHELXS2013/1 (Sheldrick, 2008), SHELXL2014/7 (Sheldrick, 2008), Mercury (Macrae et al., 2006), SHELXL2014/7 computer programs.

6.3.2 General Experimental Procedure

6.3.2.1 Synthesis of 2'-hydroxy-[1,1'-bibenzo[c]phenanthren]-2-yl ((1R,2S,5R)-2-isopropyl-5-methylcyclohexyl) carbonate (3)

1 (100 mg, 0.2 mmol), triethylamine (43 mg, 0.4 mmol) and (*1R*)-(-)-menthyl chloroformate (66 mg, 0.3 mmol) were charged in a round bottom flask with $CHCl_3$ (5 ml) and stirred the mixture at room temperature for next 2 h. Later, the disteriomeric mixture was concentrated

under vacuum and the crude mixture was purified by column chromatography on silica gel where $CHCl_3$ was used as a mobile phase. Yield 92%; mp.: 254-256ºC.

(S,R)-3a : mp.: 254-256°C, ^{1}H NMR ($CDCl_3$, 500 MHz, δ/ppm) : δ= 1.02 (3H, d, *J*=6.5 Hz), 1.09 (3H, d, *J*=7 Hz), 1.13 (3H, d, *J*=7 Hz), 1.35 (4H, m), 1.65 (2H, m), 1.82 (2H, m), 2.43 (2H, m), 4.97 (1H, dt, *J*= 4.5 Hz and 10.5 Hz), 6.10 (1H, s), 6.64 (2H, t, *J*= 8 Hz), 6.91 (3H, m), 6.91 (3H, m), 7.04 (2H, m), 7.11 (4H, m), 7.20 (1H, d, *J*=8.0 Hz), 7.29 (1H, d, *J*=8.0 Hz), 7.45 (1H, d, *J*=8.5 Hz), 7.60 (1H, d, *J*=8.5 Hz), 7.65 (1H, d, *J*=8.5 Hz). ^{13}C NMR (125 MHz, $CDCl_3$, δ /ppm) : δ = 154.33, 152.99, 148.03, 132.25, 130.68, 130.53, 130.26, 130.09, 130.05, 129.92, 129.35, 128.16, 128.14, 127.46, 127.31, 126.57, 126.07, 125.97, 125.68, 125.62, 125.42, 125.26, 125.08, 124.98, 124.90, 124.89, 124.82, 124.79, 123.94, 123.54, 123.16, 123.11, 122.82, 122.66, 119.16, 117.66, 80.11, 47.11, 41.63, 40.94, 34.15, 31.60, 26.15, 23.39, 22.06, 20.88, 16.67. HRMS (FAB) calcd for $C_{47}H_{40}O_4$ $[M]^+$ 668.2926 found 668.2926.

(R,R)-3a : mp.: 239-241°C, ^{1}H NMR ($CDCl_3$, 500 MHz, δ/ppm) : δ= 0.90 (3H, d, *J*=6.5 Hz), 0.96 (3H, d, *J*=7 Hz), 1.07 (3H, d, *J*=7 Hz), 1.40 (4H, m), 1.64 (2H, m), 1.77 (2H, m), 2.16 (1H, m), 2.50 (1H, d, *J*=11 Hz), 4.90 (1H, dt, *J*= 4.5 Hz and 10.5 Hz), 6.33 (1H, s), 6.63 (1H, d, *J*=8.0 Hz), 6.68 (1H, d, *J*=8.0 Hz), 6.91-7.11 (11H, m), 7.21 (1H, d, *J*=8.0 Hz), 7.30 (1H, d, *J*=8.0 Hz), 7.37 (1H, d, *J*=8.0 Hz), 7.44 (1H, d, *J*=8.5 Hz), 7.58 (1H, d, *J*=8.5 Hz), 7.63 (1H, d, *J*=9 Hz). ^{13}C NMR (125 MHz, $CDCl_3$, δ /ppm) : δ = 154.13, 153.13, 147.95, 132.22, 130.64, 130.49, 130.31, 130.05, 130.00, 129.47, 128.13, 127.44, 127.30, 126.58, 126.10, 125.95, 125.84, 125.67, 125.37, 125.06, 124.92, 124.77, 123.96, 123.57, 123.36, 123.22, 122.86, 122.38, 119.35, 118.19, 80.35, 46.98, 40.61, 34.18, 31.57, 26.49, 23.66, 22.14, 20.66, 16.60, 14.13. HRMS (FAB) calcd for $C_{47}H_{40}O_4$ $[M]^+$ 668.2926 found 668.2926.

(S,R)-3c : mp.: 169-171°C, ^{1}H NMR ($CDCl_3$, 500 MHz, δ/ppm) : δ = 1.01 (3H, d, *J*=6.5 Hz), 1.08 (3H, d, *J*=7 Hz), 1.12 (3H, d, *J*=7 Hz), 1.35 (4H, m), 1.65 (2H, m), 1.82 (2H, m), 2.39 (2H, m), 4.94 (1H, dt, *J*= 4.5 Hz and 10.5 Hz), 6.04 (1H, s), 6.66 (2H, t, *J*= 8.0 Hz), 7.00 (4H, m), 7.30 (1H, s), 7.34 (1H, d, *J*=8.5 Hz), 7.39 (1H, s), 7.41 (4H, m), 7.44 (1H, d, *J*=8.0 Hz), 7.47 (1H, d, *J*=8.5 Hz), 7.59 (1H, d, *J*=8.5 Hz), 7.64 (1H, d, *J*=8.5 Hz). HRMS (FAB) calcd for $C_{47}H_{38}Br_2O_4$ $[M]^+$ 824.1136 found 824.1121.

(R,R)-3c : mp.: 166-170°C, ^{1}H NMR ($CDCl_3$, 500 MHz, δ/ppm) : δ = 0.89 (3H, d, *J*=6.5 Hz), 0.94 (3H, d, *J*=7.0 Hz), 0.97 (3H, d, *J*=7.0 Hz), 1.37 (4H, m), 1.63 (2H, m), 1.78 (2H, m), 2.13 (1H, m), 2.47 (1H, d, *J*=11.0 Hz), 4.89 (1H, dt, *J*= 4.5 Hz and 10.5 Hz), 6.28 (1H, s), 6.73 (2H, m), 7.06 (4H, m), 7.29 (1H, d, *J*=8.0 Hz), 7.33 (1H, d, *J*=8.0 Hz), 7.39 (1H, d, *J*=8.0 Hz), 7.42 (5H, m), 7.46 (1H, d, *J*=8.5 Hz), 7.59 (1H, d, *J*=8.5 Hz), 7.63 (1H, d, *J*=9.0 Hz). ^{13} C NMR (125 MHz, $CDCl_3$, δ /ppm) : δ = 153.86, 153.25, 147.98, 132.17, 129.78, 129.56, 129.08, 128.55, 128.48, 127.72, 127.52, 127.32, 126.74, 126.63, 125.95, 125.56, 125.37, 125.24, 125.12, 124.74, 123.99, 123.76, 123.26, 120.65, 119.51, 119.15, 117.46, 80.53, 46.99, 40.61, 34.14, 31.57, 29.70, 26.53, 23.69, 22.14, 20.63, 16.61. HRMS (FAB) calcd for $C_{47}H_{38}Br_2O_4$ $[M]^+$ 824.1136 found 824.1121.

6.3.2.2 Synthesis of [1,1'-bibenzo[c]phenanthrene]-2,2'-diol (2)

The diastereomers **(*S,R*)-3a** (56 mg, 0.084 mmol) and **(*R,R*)-3a** (44 mg, 0.065 mmol) were separately mixed with 1M KOH (2 ml) in two different round bottom flask and refluxed with EtOH at 85°C for 20 h. Later, 6 N HCl was added to the reaction mixture to neutralize the solution and the products **(*S*)-2a** and **(*R*)-2a** were extracted by chloroform (10 ml × 3). Next, the organic phases were dried over anhydrous Na_2SO_4 and concentrated in rotary. Eventually, we obtained excellent yields of each enantiomers of **2a** (>99% yield). The hydrolyzed products were used for next reaction.

6.3.2.3 Synthesis of 2H,2'H-[1,1'-bibenzo[c]phenanthrenylidene]-2,2'-dione (1)

(*S*)-2a (40 mg, 0.082 mmol), CuCl(OH) –TMEDA (2.32 mg, 0.001 mmol) ethanol (2.5ml) were charged in a round bottom flux and gently stirred at room temperature in an open air for 20h to produce our desire product . Finally, the product was filtered and washed by ethanol to obtain fine red solid crystal of **(*P*)-1a (**86% yield).

And, **(*R*)-2a** (35 mg, 0.072 mmol), CuCl(OH) –TMEDA (2.32 mg, 0.001 mmol) ethanol (2.5ml) were charged in a round bottom flux and gently stirred at room temperature in an open air for 20h to produce our desire product . Finally, the product was filtered and washed by ethanol to obtain fine red solid crystal of **(*M*)-1a (**82% yield).

❖ ***For spectroscopic data of 1a, 1c and 2a, 2c please see chapter 2 and chapter 3.***

6.4 CONCLUSION

In summary, I have developed an efficient synthetic approach and resolution of the new BIPOL (***S***)-**2a, 2c** and (***R***)-**2a, 2c** compounds. I also synthesized the corresponding quinone derivatives (***P***)-(+)-**1a, 1c** and (***M***)-(-)-**1a, 1c** as well with high optical purity. I also demonstrated that (*1R*)-(-)-menthyl chloroformate acid chloride was a suitable resolving agent for the helically chiral BIPOL. These BIPOL's (***S***)-**2a, 2c** and (***R***)-**2a, 2c** can serve as an asymmetric catalyst in organic synthesis. Work in this field is currently in progress in my laboratory.

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CHAPTER 7

Application of the amphiphilic oxa[9]helicene derivatives in Langmuir-Blodgett (LB) films

Synopsis

Synthesis of amphiphilic oxa[9]helicene derivatives and their practical use on thin film using Langmuir-Blodgett (LB) film deposition technique was done. Some of the amphiphilic oxa[9]helicene derivatives shown exceptional ability to form thin layer on silica surface which was confirmed by π-A isotherm.

CHAPTER 7

7.1 INTRODUCTION

Application of organic compounds in modern electronic devices is not a new idea. For the last five decades research interest on organic electronics is exponentially growing because, organic compounds have variable functional characteristics. The important features of organic materials are the low cost, and reasonably mild reaction conditions for thin film formation. Although a large number of organic materials are using in thin film formation but most recently polycyclic aromatic compounds paid the more attention in the preparation of next-generation electronic materials. In general, polycyclic aromatic compounds have large π-conjugation systems and this feature makes it as a key materials in electronic and optoelectronic devices, such as organic light emitting diode (OLED) materials,[1] organic field-effect transistors (OFET), [2] organic thin-film transistor[3] and so on.

Helicene molecules are *ortho*-fused polycyclic aromatic compounds. Due to the *ortho*-fused aromatic rings, helicene molecules possess large π-conjugated systems. One of the most interesting features of helicene molecules is their chirality although they do not have any asymmetric carbons and chiral centers. The chirality arises due to the steric interaction of the terminal rings. Literature survey revealed that, helicene molecules have co-facial staking ability and in Langmuir-Blodgett (LB) films, they form hexagonally macroscopic fibers like aggregates.[4]

Some studies have also shown that, the co-facial stacking of helicene molecules with the relatively large π-conjugated system can provide higher charge mobility because of large orbital-orbital overlapping among neighboring molecules.[5] That is why, it is expected that the helicene co-facial stacking behave like nano wires with the one-dimensional transport of charge carriers achieved via larger overlapping between π-conjugated systems. More recently, a [5]helicene derivative (3,12-dimethoxy-7,8-dicyano[5] helicene) was successfully used as a novel emissive material in an organic light emitting diode (OLED) and it showed high current efficiency.[6] In 2015, Storch and co-workers synthesized imidazole based [6] helicene derivative (1-butyl-3-(2-methyl[6]-helicenyl) imidazolium bromide) and deposited its films on SiO_2 substrates for the development of organic molecular semiconducting devices and the construction of a fully reversible humidity sensor.[7] But according to the best of our knowledge, the semiconducting applications of oxa[9]helicene or their derivatives have never

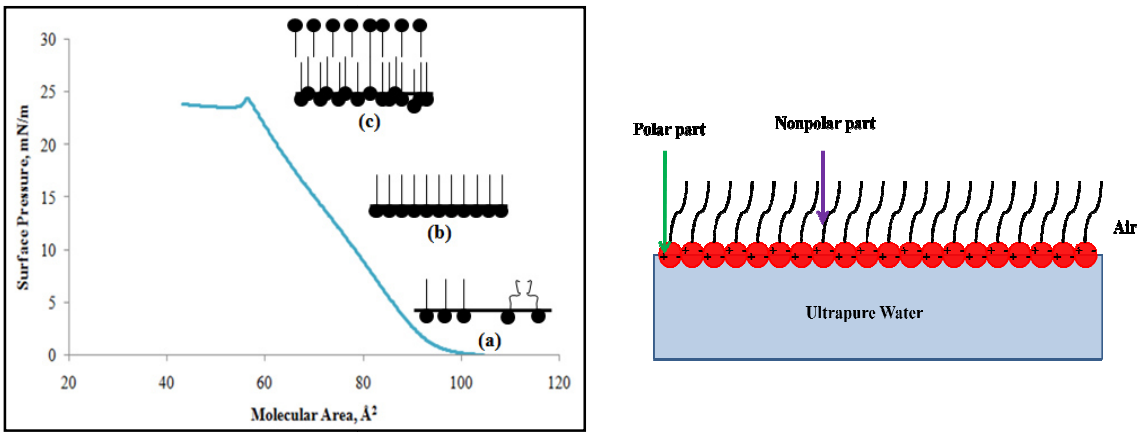
been revealed. This chapter fully based on deposition of monolayer and π-isotherm. The characterization and other optical properties of thin films were done by collaboratively with Prof. Iimura's research group.

7.2 RESULTS AND DISCUSSIONS

In general, oxa[9]helicene molecules are less soluble in polar solvent, but when ethylene glycol molecules are introduced into helicene moiety then it expected to improve its solubility and amphiphilic character as well. In chapter 5, we have described the synthesis of some novel amphiphilic oxa[9]helicene derivatives; e.g. hydroxy-11-oxa[9]helicene (**9**), 9-ethyleneglycoxy-11-oxa[9]helicene (**10**), 9-triethyleneglycoxy-11-oxa[9]helicene (**11**), 9-hexaethyleneglycoxy-11-oxa[9]helicene (**12**), 9-diethyleneglycoxy-11-oxa[9]helicene (**13**), 9-tetraethyleneglycoxy-11-oxa[9]helicene (**14**), 1,1'-bibenzo[c]phenanthrene]-2,2'-diol (BIPOL) and Oxa[9] helicene.

All the compounds are highly soluble in $CHCl_3$ and form homogeneous Langmuir-Blodgett (LB) monolayer at the air-water interface. A plot of the surface pressure as a function of the area of water surface available to each molecule gives the single most important indicator of the monolayer properties. This is carried out at constant temperature and is accordingly known as a surface pressure / area isotherm or π-A isotherm. A number of distinct regions are immediately apparent on examining the isotherm (Figure 7.1A). As the surface area is reduced from its initial high value Figure 7.1, (a)-region: gas phase), there is a gradual onset of surface pressure until an approximately horizontal region is reached (Figure 7.1, (b)-region: solid phase). In the horizontal region, the hydrophobic part (Figure 7.1B) which were originally distributed near the water surface. At the surface area of just over 65 $Å^2$molecule^{-1} there is an abrupt increase of slop. This is clearly also due to a phase change and represents a transition to an ordered solid-like arrangement of the two dimensional array of molecules (Figure 7.1A-(b) region). At smaller surface areas the phenomenon of collapse occurs and the compressibility approaches infinity. The onset of collapse depends greatly on such factors as the rate at which the film is being compressed. In this type of collapse it is believed that

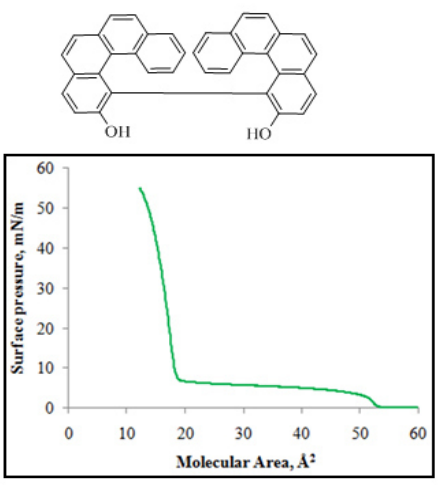
molecular layer are riding on top of each other and disordered multilayers are being formed (Figure 7.1A-(c) region).



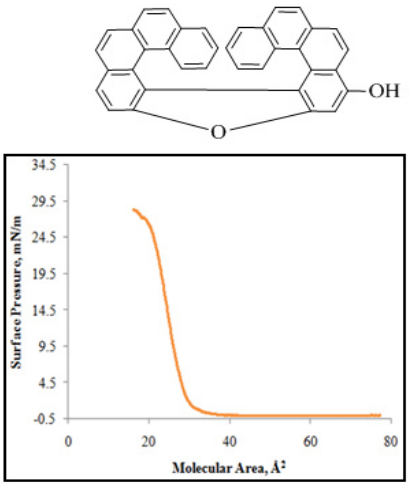
(A) **(B)**

Figure 7.1 (A) Surface pressure/Area isotherm at different phases: **(a)** Coexistence of solid and gas phase; **(b)** Solid phase and **(c)** Collapsed phase; **(B)** Molecular orientation at air / water inter-phase

synthesized amphiphilic oxa[9]helicene derivatives **9, 10, 11, 12, 13, 14** along with some other helicene like molecules were formed homogeneous monolayer at air-water interface. The monolayer was confirmed by surface pressure/area (π-A) isotherm (Figure 7.2). Later, the monolayers of different compounds were successfully deposited on FTO coated glass substrate using Langmuir-Blodgett (LB) film deposition method. The films were characterized using different spectroscopic techniques and finally we were able to show that, the synthesized compounds are good candidate in semiconducting devices.[8, 9]



(BIPOL)



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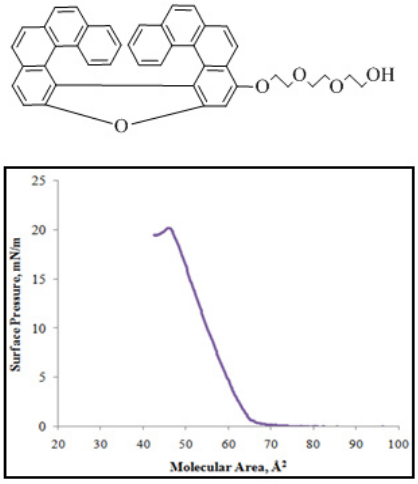

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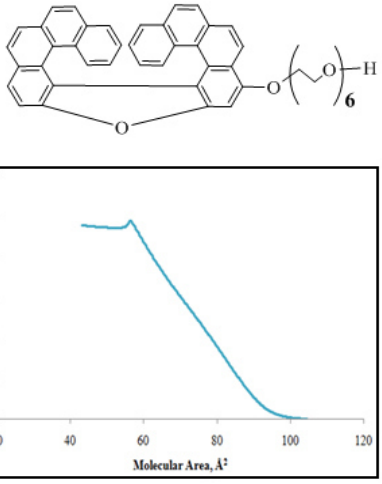

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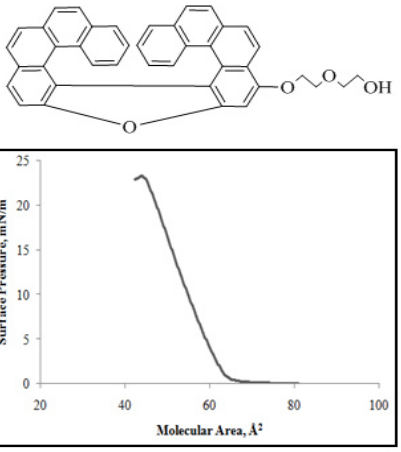

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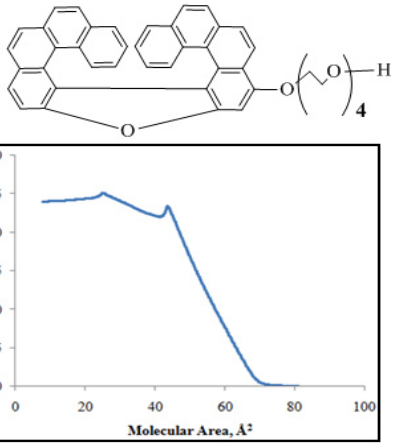

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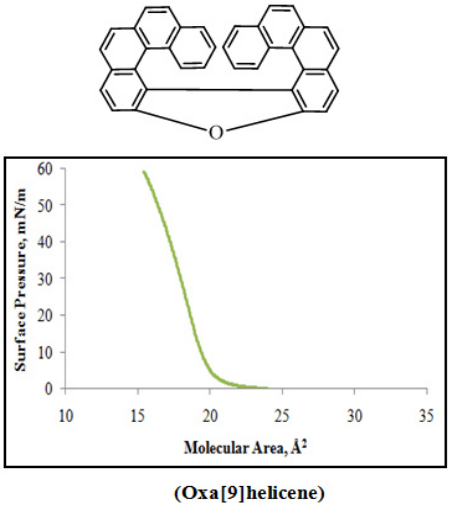

Figure 7.2 Surface pressure/Area isotherm of **9, 11, 12, 13, 14,** BIPOL and oxa[9]helicene at constant temperature (25ºC).

7.3 CONCLUSION

In this chapter, I have successfully shown that, the amphiphilic **9, 11, 12, 13, 14** along with BIPOL and oxa[9]helicene compounds form nice LB film at air-water interface which was confirmed by Surface pressure/Area isotherm. Further development of the new amphiphilic compounds and enhancement of the optical properties are ongoing process.

7.4 REFERENCES

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CHAPTER 8

Summary and Appendix

CHAPTER
8

8.1 SUMMARY

Helicenes are polycyclic aromatic compounds formed from ortho-annulated benzene or other aromatic rings. Due to the steric strain of the terminal rings, the molecules change its shape from planner to non-planner screw shaped skeletons. Although helicenes do not have any chiral centers but they show axial chirality. Helicene's chirality arises from the steric hindrance between the terminal rings, which secure the helical structure either the clockwise and anticlockwise direction. . The chemistry of screw shaped helical molecules apprehends interest in advance research field. At present time, helicenes and helicene like molecules can be used as organic semiconductors in different range of optoelectronic devices including organic light emitting transistors, photodiodes, and phototransistors. Besides this, helical molecules also used as, asymmetric catalysis, chiral molecular recognition, molecular machines, liquid crystals and so on.

In general, helicene molecules are classified in two different categories one is carbohelicenes and another one is heterohelicene. Early research work on helicene chemistry was mainly focused on carbohelicenes but, recently due to interesting properties and wide range of applications, research on heterohelicene (e.g. thia-, sila-, aza- and oxahelicene) has gained tremendous interest. According to the literature survey, it is shown that, incorporation of heteroatoms in the helical skeleton enhances the optical and electronic properties of the molecules. For the last two to three decades, significant surveillance has been committed to thiahelicenes and azahelicenes. However, in case of oxa[n]helicenes less attention was paid compare to other heterohelicenes.

This thesis deals with different effective synthetic methods of the synthesis of helicenes and helicene like molecules, optical separation of helicene derivatives and potential applications of amphiphilic helicene derivatives on solar cell system.

The conversion of phenols into bi-phenol derivatives has been utilized for the synthesis of many important natural compounds and chiral ligands such as BINOL and its related derivatives. On the other hand, the oxidative coupling reactions of phenols also generate quinone derivatives, which are formed by further oxidation of bi-phenol derivatives. The quinone derivatives have long been regarded as an undesired byproduct of the oxidative

coupling reaction of phenols. Considerable attention has been focused on the study and application of bi-phenol derivatives. However, the investigation of the corresponding quinone derivatives is limited. In particular, the 2,2'-diphenoquinone derivatives which are synthesized by the oxidation of 2,2'-biphenols, are less studied compared to the 4,4'-diphenoquinone derivatives. My synthetic approach is the best-fitted method for the synthesis of helical shaped quinone derivatives **5a-g** in excellent to good yield by oxidative coupling of 2-hydroxybenzo[*c*]phenanthrene derivatives (Chapter 2). The quinone derivatives were used throughout the research work.

The helical quinone derivatives later subjected into reduction process. At the beginning, different reducing agents were applied for the reduction of non-substituted quinone. Among them 5% Pd-C catalyst showed the best result. Later the 5% Pd-C catalyst used for the other substituted quinone derivatives reduction and I obtained excellent yield. But in case of 8H,8'H-[7,7'-Bibenzo[c]chrysenylidene]-8,8'-dione and 14,14'-Dibromo-8H,8'H-[7,7'-bibenzo[c]chrysenylidene]-8,8'-dione the reduced products are not stable at all. Because, when I tried to recrystalize the reduced products in ethyl acetate solvent the resulting crystals were the starting quinone derivatives**,** which was confirmed by the ^{1}H NMR spectra data analysis (Chapter 3).

Haloaryl compounds are commonly used for many types of cross-coupling reactions such as Suzuki-Miyaura, Mizoroki-Heck, Sonogashira etc. My next attempt was to synthesized the halo-substituted oxa[9]helicenes by the reaction of the helical quinones with various halogenating reagents. The results for chloro substituted oxa[9]helicenes was outstanding and the yield was excellent as well. But in case of bromo substituted oxa[9]helicene derivatives the results were not satisfactory. The bromination reaction was only proceeded for 1,1'-Bibenzo[c]phenanthrylidene-2,2'-dione and 6,6'-Dibromo-1,1'-bi[benzo[c]phenanthrenylidene]-2,2'-dione along with non-substituted oxa[9]helicene as a side product. One of the fascinating product was isolated during the bromination reaction in good yield. When I used NBS as a brominating reagent the product was not our desire bromo substituted oxa[9]helicene it was dibromo substituted spiro-lactone compound. Later, the molecular configuration was confirmed by X-ray crystallographic data analysis and I also proposed a possible reaction mechanism for that reaction (Chapter 4).

Optically pure compounds play the key role in medicinal chemistry but now a day, chiral compounds are intensively studies on chiral photonics such as quantum optics and optical

spintronics. In helicene chemistry, isolation of optically pure compounds is quite rare and very few literatures are available on online. In my research work, I have synthesized a new class of amphiphilic oxa[9]helicene derivatives in good to very good yields and using chiral HPLC I have also successfully separated the enantiomers with high optical purity (Chapter 5).

Asymmetric synthesis in organic chemistry is one of the challenging topics. Our research group in 2014 had shown that using chiral amines with Cu it is possible to obtain high enantiomerically pure quinone derivatives. The results shows in case of non substituted quinone only 67% *ee* of *M*-isomer and 66% *ee* of *P*-isomer were obtained. In my research, I have successfully shown the optical resolution of quinone derivatives through diastereomer formation using (*1R*)-(-)-menthyl chloroformate as a chiral resolving agent. The diastereomers were separated through preparative recycling HPLC (Chapter 6) and after hydrolysis followed by catalytic oxidation I obtained 100% *ee* of *P*-isomer along with >99% *ee* of *M*-isomer.

My research group has strong collaboration with soft material laboratory in our university. I have successfully applied some of my synthesized amphiphilic oxa[9]helicene derivatives on Langmuir–Blodgett (LB) film through this collaboration. The amphiphilic oxa[9]helicene derivatives shown fascinating optical properties. In near future it might be used in different optoelectronics devices (Chapter 7). Further enhancement and modification of the amphiphilic oxa[9]helicene derivatives is my next interest and I am currently working on that field.

8.2 APPENDIX

8.2.1 Published papers

1. **Title:**
   Synthesis of helical quinone derivatives from oxidative coupling of substituted 2-hydroxybenzo[*c*]phenanthrenes.; **Mohammad Shahabuddin**, Akira Akutsu, Takao Kimura, Michinori Karikomi, *Synthesis,* **2017**, *49*, 1547–1554.

2. **Title:**

   A novel synthesis of halogenated oxa[9]helicenes and dibromo spiro lactone derivative by the reaction of the helical quinones with several halogenating regents.; **Mohammad Shahabuddin**, Mohammad Salim, Masaaki Tomura, Takao Kimura, Michinori Karikomi; *Tetrahedron Lett.* **2016**, *57(52)*, 5902–5906.

3. **Title:**

   Synthesis, chiral resolution and optical properties of amphiphilic oxa[9]helicene derivatives.; **Mohammad Shahabuddin**, Md Jalil Miah, Ken-ichi Iimura, Takao Kimura, Michinori Karikomi.; *Tetrahedron lett.* **2017**, *58(13)*, 1334–1337.

4. **Title:**

   Structural and Photoelectrical Characterization of Thin Films of a Novel Amphiphilic Oxa[9]helicene Derivative. ; Md Jalil Miah, **Mohammad Shahabuddin,** Michinori Karikomi, Mohammad Salim, Eri Nasuno, Norihiro Kato, Ken-ichi Iimura; *Bull. Chem. Soc. Jpn*. **2016**, *89*, 203–211.

5. **Title:**

   Fabrication and Characterization of Molecular Films of 11-Oxa[9]helicene and 9-Diethyleneglycoxy-11-oxa[9]helicene.; Md Jalil Miah, **Mohammad Shahabuddin**, Md. Nazmul Kayes, Michinori Karikomi, Eri Nasuno, Norihiro Kato, Ken-ichi Iimura; *Trans. Mat. Res. Soc. Jpn*. **2016***, 41(2)*, 151–154.

8.2.2 Conferences

1. **Title:**

   Synthesis of spiro lactone by the reaction of helical quinone derivatives with several halogenating reagents.; **Shahabuddin, Mohammad**; Salim, Mohammad; Kimura, Takao; Karikomi, Michinori; The 96th Annual Meeting 2016 of CSJ (March: 24-27), Presentation No: **2PB-056**.

2. **Title:**

   Synthesis of helical quinone derivatives by use of optically active bis-oxazoline ligands.; **Shahabuddin, Mohammad**; Tanaka, Yoshiaki; Kimura, Takao; Karikomi, Michinori; The 96th Annual Meeting 2016 of CSJ (March: 24-27), Presentation No: **2PB-063**.

3. **Title:**

   Optical resolution of helical quinone derivatives through diastereomeric process; **Shahabuddin, Mohammad**; Kimura, Takao; Karikomi, Michinori; The 97th Annual Meeting 2017 of CSJ at Keio University, Yokohama, Japan. Date: 16-19 March 2017. Presentation No: **3F1-13**.

4. **Title:**

   Study of Thin Films of Oxa[9]helicene Derivatives and Explore Their Photoelectrochemical Properties.; Md Jalil Miah, **Mohammad Shahabuddin,** Mohammad Salim, Md. Nazmul Kayes, Michinori Karikomi, Eri Nasuno, Norihiro Kato, Ken-ichi Iimura, The 25th Annual MRS-J2, At Yokohama, Volume: **C3-O9-006**.

5. **Title:**

   Thin Films of Oxa[9]helicene Derivatives and Their Photoelectrochemical Properties.; Md Jalil Miah, **M. Shahabuddin,** M. Salim, Md. N. Kayes, M. Karikomi, E.Nasuno, N. Kato, K. Iimura, The 34th Annual Meeting on Photochemistry of Solids and Surfaces, At Utsunomiya University, Volume: **106**.

6. **Title:**

   Fabrication of LB monolayers of Oxa[9]-helicene Derivatives and Their Photo-electrochemical properties.; Md Jalil Miah , **Mohammad Shahabuddin,** Mohammad Salim, Michinori Karikomi, Eri Nasuno, Norihiro Kato, Ken-ichi Iimura; The 95th CSJ Annual Meeting, At Nihon University, Volume: 1, **C2-12**.

7. **Title:**

   Structural Characterization of Thin Films of Oxa[9]helicene Derivatives Prepared by Langmuir Technique and Spin Coating Method.; Md Jalil Miah, **Mohammad Shahabuddin**, Md. Nazmul kayes, Michinori Karikomi, Eri Nasuno, Norihiro Kato, ken-ichi Iimura.; The 67th Divisional Meeting on Colloid and Interface Chemistry at Hokkaido, Japan. Date: 22-24 September 2016. Presentation No: **3F08**.

8. **Title:**

   Preparation and Characterization of Thin Films of an Axially Chiral Bibenzo[c]phenanthrene Diol.; Md. Nazmul kayes, Md Jalil Miah, **Mohammad Shahabuddin**, Michinori Karikomi, Eri Nasuno, Norihiro Kato, ken-ichi Iimura.; The 67th Divisional Meeting on Colloid and Interface Chemistry at Hokkaido, Japan. Date: 22-24 September 2016. Presentation No: **PI-013**.